AL/OE-TR-1994-0131

NOISE-INDUCED SLEEP DISTURBANCE IN
RESIDENTIAL SETTINGS

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SUBJECT: Missing Pages

Enclosed are three pages 14, 18, and 30 which were inadvertently omitted from a publication titled, "Noise Induced Sleep Disturbance in Residential Settings" recently sent to you by our office.

SIGNED

Robert A. Lee
Noise Effects Branch

Attachments:
Pages 14, 18, and 30 from AL/OE-TR-1994-0131

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AL/OE-TR-1994-0131

The voluntary informed consent of the subjects in this research was obtained as required by Air Force Regulation 169-3.

This technical report has been reviewed and is approved for publication.

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FOR THE DIRECTOR

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The present study observed the effects of nighttime noise exposure on the in-home sleep of residents of neighborhoods near one military airbase and one civil airport, and in several households with negligible nighttime aircraft noise exposure. Test participants pressed a button upon awakening for any reason, whatsoever, after retiring for the evening. A total of 1887 subject-nights of data were collected. A statistically reliable relationship was observed between sound exposure levels of noise intrusions in sleeping quarters and behaviorally confirmed awakenings. The average rate of spontaneous (non-noise related) awakenings among test participants at all sites was approximately two per night.

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1 EXECUTIVE SUMMARY

1.1 Goal and Design of Study

The present study observed the effects of nighttime noise exposure on the in-home sleep of residents of neighborhoods near one military airbase and one civil airport, and in several suburban households with negligible nighttime aircraft noise exposure. The basic goal was to collect data to aid construction of a readily interpretable and defensible dosage-response relationship summarizing noise-induced awakening. Test participants were solicited among residents of a neighborhood near Castle Air Force Base (in Merced, CA) which had been exposed for many years to large numbers of high noise level nighttime aircraft operations. Test participants near Los Angeles International Airport (LAX) were solicited from a neighborhood exposed to aircraft operations of lower noise level. Test participants in neighborhoods which served as control sites were not exposed to aircraft noise at night, but were exposed to high levels of road traffic noise.

Outdoor Day-Night Average Sound Levels (DNL) at the homes of test participants at Castle Air Force Base were on the order of $L_{dn} = 80$ dB. DNL values near LAX were on the order of $L_{dn} = 66$ dB. DNL values at the former site varied from about 90 dB on weekdays to about 50 dB on weekends, due to the absence of nighttime training operations on weekends. DNL values at test participants' homes near LAX varied over a much smaller range (from about 60 to 70 dB). DNL values averaged about 60 dB at control sites, but ranged from about 50 to 70 dB.

A behavioral indication of sleep disturbance was selected as most appropriate for the goals of this study. Test participants were instructed to press a button upon awakening for any reason whatsoever after retiring for the evening. They were also asked to answer several sleep-related questions just prior to retiring for the night, and to answer several questions immediately after awakening in the morning. A palmtop computer was used to register and timestamp this behavioral and attitudinal information. Indoor noise levels in each test participant's customary sleeping quarters were monitored by automated instrumentation from 10:00 PM to 8:00 AM, as were outdoor noise levels in the vicinity of several test participants' homes. Noise monitors recorded continuous time histories of A-weighted sound levels, numbers of events exceeding sound level thresholds, and half-second A-weighted time histories of events.

1.2 Data Collection

A total of 1887 subject-nights of observations were collected. Thirty-eight men and 47 women, ranging in age from 19 to 79 years (mean age = 47 years), living in 45 different homes, participated in the current study. Test participants' duration of residence at the data collection sites ranged from 2 months to more than 40 years, with a mean of about 12 years.

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1.3 Data Analyses

Three primary analyses were undertaken of the association of noise exposure with behavioral indications of sleep disturbance in these data:

- "noise event-based" (prospective) analyses,
- "awakening-based" (retrospective) analyses, and
- "entire night" analyses.

The **noise event-based** analyses sought awakening responses within periods of one, two and five minutes *after* the occurrence of noise events exceeding site-specific level and duration thresholds. The **awakening-based** analyses attempted to associate sleep disturbance with noise measured in one, two and five minute epochs *prior to* the occurrence of awakenings. **Entire night** analyses were conducted on noise measures and both behavioral and self-report responses to a whole night's sleep.

Supplementary analyses, including logistic multiple regressions, were undertaken to investigate relationships between nonacoustic factors and awakening data, and to examine relationships between self-report and behavioral indications of sleep disturbance.

1.4 Results of Noise Measurements

As shown in Figure 1, the higher centiles of the distributions of nighttime indoor noise event levels at Castle Air Force Base exceeded those at LAX and control sites by as much as two orders of magnitude. Indoor levels of nighttime noise intrusions produced by street and/or highway traffic at control sites were comparable in level to the indoor levels of noise intrusions produced by aircraft operations at LAX.

1.5 Behavioral Awakening Responses

Only 326 behavioral awakening responses occurred within five minutes of occurrence of 10,096 noise events. Another 4126 behavioral awakening responses (non-noise induced, or "spontaneous" awakenings) were recorded at other times. Thus, only one in about 14 awakenings were directly attributable to noise exposure. Figure 2 shows the distribution of behavioral awakening responses related to noise events for all subject-nights and all sites. Figure 3 shows the distribution of spontaneous awakening responses throughout the study at all sites. (Note that the bars in these figures represent numbers of subject-nights during which a given number of awakening responses occurred, *not* the total number of awakening responses.)
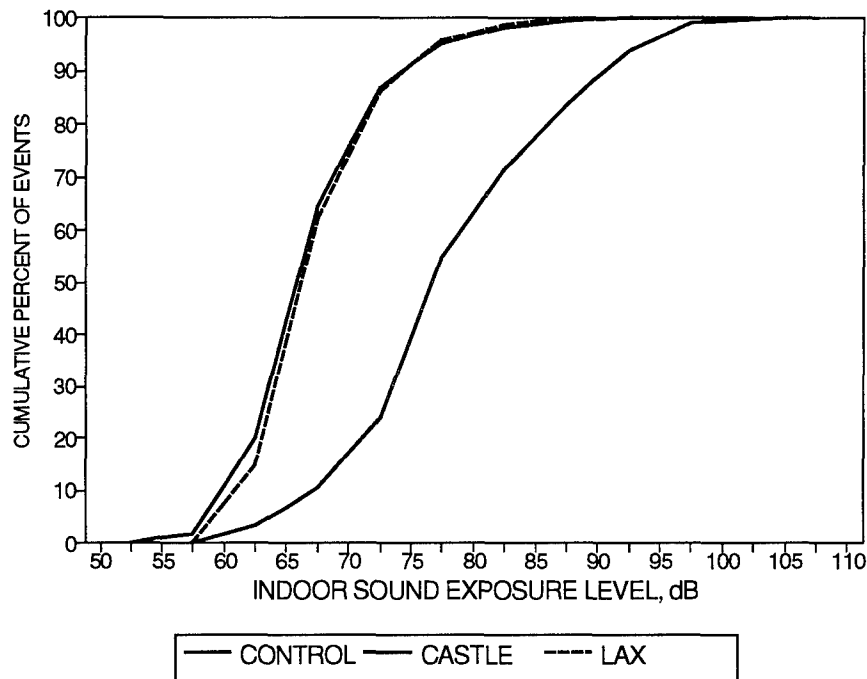
Figure 1 *Example of cumulative distributions of indoor noise event levels at three study sites.*

1.5.1 Results of noise event-based analyses of behavioral awakening responses

Figure 4 shows a dosage-response relationship derived from noise event-based analyses. The prevalence of awakening associated with noise events of an indoor SEL on the order of 70 dB is 1.6%. An increase of 1.6% in prevalence of awakening is predicted for each 10 dB increase in SEL.

1.5.2 Results of epoch-based analyses of behavioral awakening responses

As seen in Figure 5, the dosage-response relationship derived from epoch-based analyses resembles that derived from event-based analyses. The rate of increase in prevalence of awakening with increasing SEL was somewhat smaller, however, for the relationship derived from epoch-based analyses, and the association was not as strong. The prevalence of awakening within a 1-minute epoch of $L_{eq} = 40$ dB is less than 0.5%. Each 10 dB increase in noise exposure is predicted to increase the prevalence of awakening by about 0.25%.

1.5.3 Results of entire-night analyses of behavioral awakening responses

None of the entire-night noise exposure measures accounted for more than 1% of the variance in behavioral and self-report data.
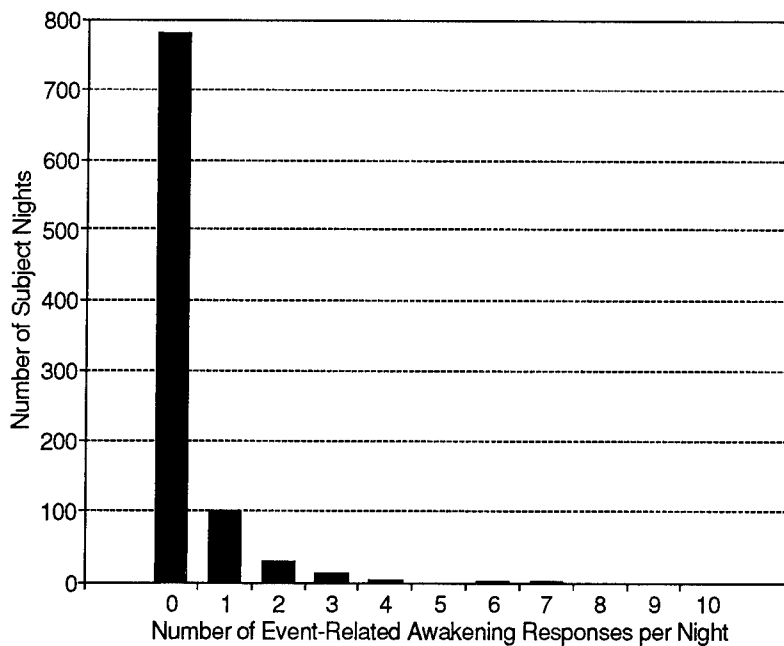
Figure 2 *Distribution of numbers of noise event-related behavioral awakening responses over subject-nights and sites.*

1.6 Results of Additional Analyses

- Prediction of awakening from combined (acoustic and other) information:

A predictive model of awakening was constructed by logistic multiple regression of acoustic and other information. Prediction of awakening was enhanced beyond that provided by sound exposure level alone by taking into consideration ambient noise levels in sleeping quarters, spontaneous awakening rates (as a surrogate for susceptibility to awakening), time since retiring, duration of residence (as a surrogate for habituation), self-reported tiredness the previous night, and age. The analysis allowed evaluation of the unique contributions to prediction of each variable, holding all other variables constant.

The likelihood of awakening was increased by increasing time since retiring, duration of residence, and tiredness on retiring. The likelihood of awakening was decreased by higher ambient level in sleeping quarters, spontaneous awakening rate, and age. The single most reliable predictor of behavioral awakening was time since retiring. Sound exposure level accounted for less variance in awakening than did other variables combined.

- Prediction of self-reported annoyance:

Annoyance due to aircraft noise was reliably associated with measures of sleep disturbance as a whole, but only 12% of the variance in annoyance ratings was predictable. Further, no reliable

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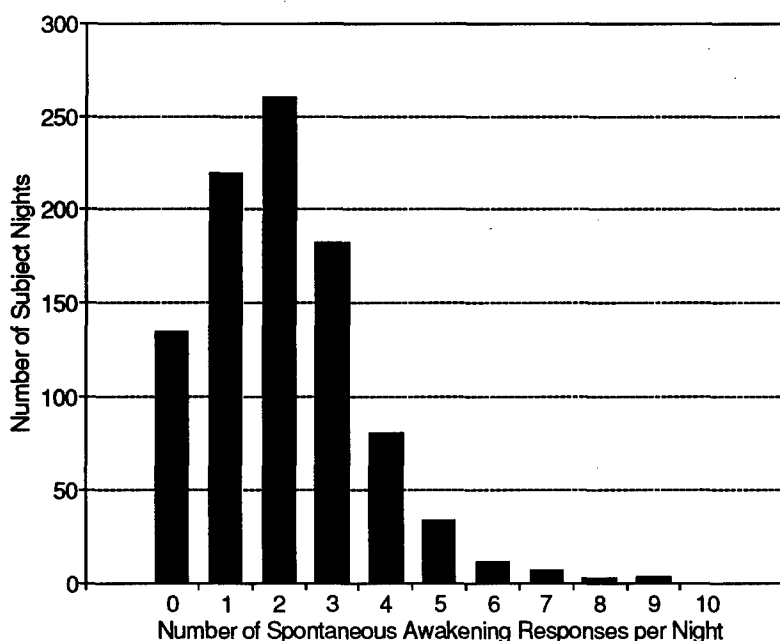
Figure 3   *Distribution of the numbers of non-noise related behavioral awakening responses over subject-nights and sites.*

association was found between nighttime L_{eq} and the prevalence of a consequential degree of annoyance.

- Differences in awakening associated with changes in noise exposure levels:

Logistic multiple regression analysis was used to compare awakening rates on weekend and week nights at Castle AFB, at which no nighttime training operations were conducted on weekends. No reliable differences were observed between awakening rates on weekend nights and week nights. However, a reliable difference was observed in annoyance due to weeknight and weekend aircraft noise exposure.

1.7 Summary of Principal Findings

Because no effort was made to rigorously define a population exposed to nighttime noise exposure, nor to obtain a representative sample of any such population, conclusions drawn from the present study apply strictly only to test participants. To the extent that generalizations are made from the present findings, they should be restricted to the effects of noise on the sleep of long term residents of areas with stable nighttime noise exposure. The following are among the major findings of the present study:

- A statistically reliable relationship was observed between sound exposure levels of noise intrusions in sleeping quarters and behaviorally confirmed awakening within five minutes

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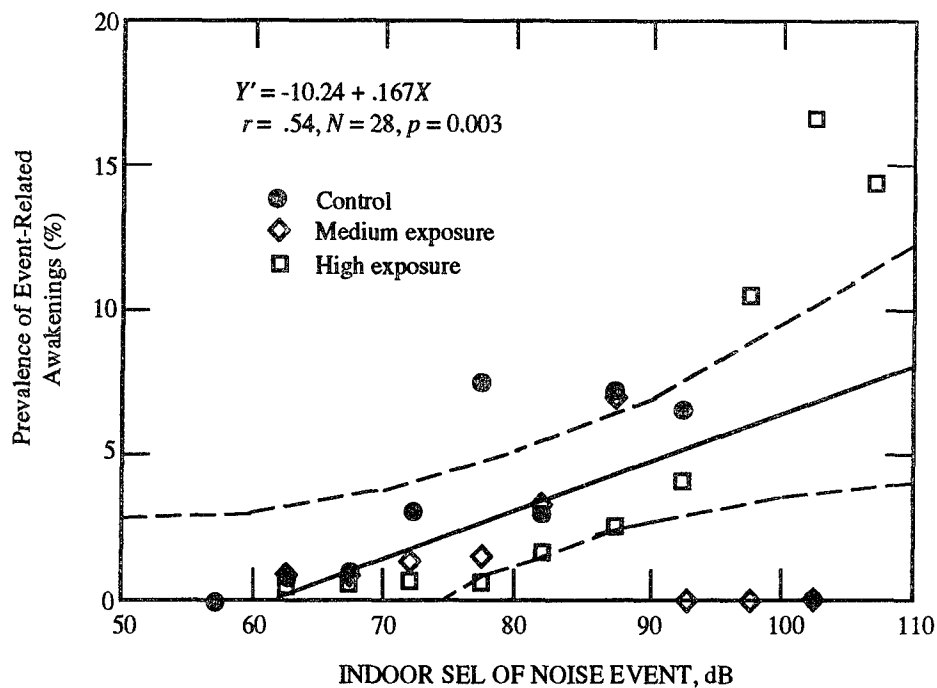
Figure 4   *Prevalence of awakening responses within five minutes of noise events, aggregated by test participants within sites, in 5dB increments. Dashed lines bound the 95% confidence interval.*

of occurrence of noise intrusions. This relationship accounted for only 30 percent of the variance in awakening data, however.

- Although test sites varied in outdoor noise exposure level over the range of levels of principal interest for environmental analysis purposes, the prevalence of awakening among test participants did not increase greatly with sound exposure levels of noise intrusions in sleeping quarters.

- Of a total of 4452 awakening responses, only 326 could be associated with noise events (that is, the behavioral awakening responses occurred within 5 minutes after the occurrence of a noise event).

- The average spontaneous rate of behaviorally confirmed awakenings among test participants at all sites was approximately two per night. This figure did not differ significantly across sites with varying levels of nighttime noise exposure.

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The chart shows:
- Y-axis: Prevalence of Epoch-Related Awakenings (%), ranging from 0 to 20
- X-axis: INDOOR LEQ OF EPOCH PRIOR TO AWAKENING, dB, ranging from 20 to 90

$Y' = -.630 + .026X$
$r = .43, N = 40, p = 0.005$

● Control
◇ Medium Exposure
□ High Exposure
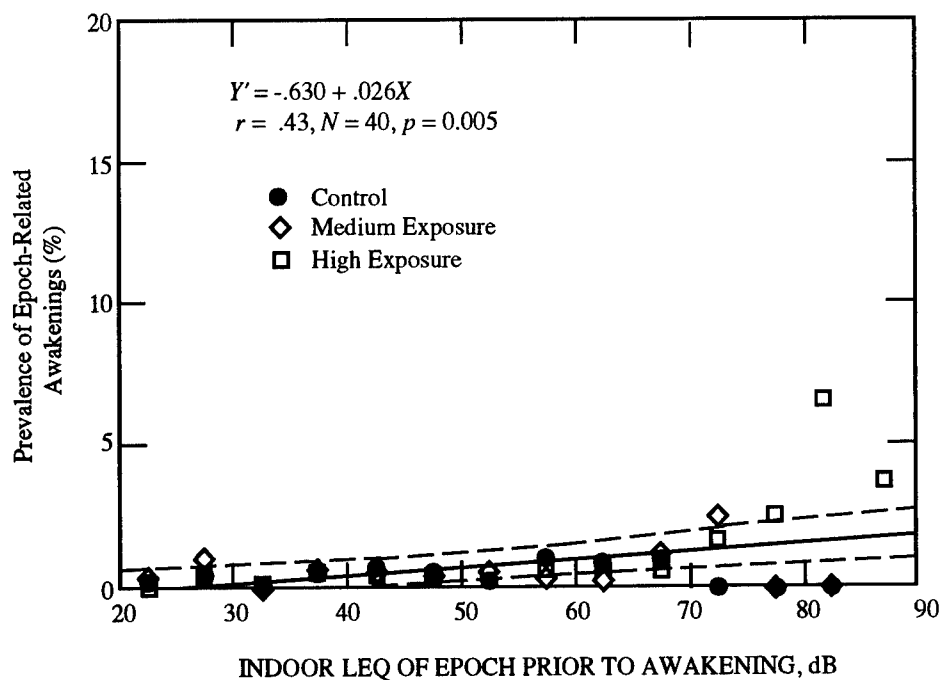
Figure 5 *Prevalence of awakening responses as a function of L_{eq} of prior one minute epoch, aggregated by test participants within sites, in 5dB increments. Dashed lines bound the 95% confidence interval.*

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2 INTRODUCTION

2.1 Purpose of Study

The U.S. Air Force and other federal agencies have been concerned for several decades with prediction and assessment of community response to noise exposure produced by aircraft operations. Although considerable progress has been made in understanding and quantifying the prevalence of noise-induced annoyance in communities, quantitative understanding of noise-induced sleep disturbance is less advanced. Limited quantitative understanding of the effects of community noise on sleep makes it difficult for Air Force environmental planners to comply with environmental impact assessment requirements of the National Environmental Policy Act of 1969.

As described in greater detail in Chapter 3, the best known dosage-response relationship for noise-induced sleep disturbance (that of FICON, 1992) is heavily influenced by the findings of small scale laboratory studies. The current study was undertaken to help relieve the scarcity of information about noise-induced sleep disturbance in residential settings. The overall goal was to collect information useful for constructing a readily interpreted dosage-response relationship summarizing the effects of noise on the in-home sleep of residents familiar with neighborhood noise environments.

Several secondary goals were intended to enhance the interpretability of the desired dosage-response relationship. These included identification of metrics and transformations of sleep disturbance data closely associated with acoustic predictor variables, identification of factors other than noise exposure which might aid prediction of sleep disturbance, and comparisons of the present findings with those of prior studies.

2.2 Organization of Report

Chapter 3 contains background information about the study of noise-induced sleep disturbance. Chapter 4 describes the procedures used in site selection, instrumentation to collect response and noise data, selection of test participants, and the data analysis plan. Chapter 5 presents data analyses and results. Chapter 6 discusses the findings, and Chapter 7 presents the conclusions drawn from them.

Appendix A describes the organization of a database for storage, retrieval, and processing of information produced in the current study. Appendix B contains information about recruiting procedures, instructions to test participants and questions for evening and morning interviews. Appendix C provides details about identification of the analysis epoch for sleep disturbance. Appendix D provides a summary of the interview data.

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3 BACKGROUND

This Chapter describes the rationale for the design of the present study in the context of a brief discussion of research methods, analytic approaches, and findings of prior studies of the effects of noise exposure on sleep.

3.1 Interpretation of Prior Findings of Noise-Induced Sleep Disturbance

The Federal Interagency Committee on Noise has adopted the dosage-response relationship seen in Figure 6 as a summary of the effects of noise on sleep. A recent review of the quantitative literature on noise-induced sleep disturbance (Pearsons, Barber, and Tabachnick, 1989) found substantial differences between the results of 16 laboratory and five field studies, as summarized in Figure 7. Pearsons *et al.* concluded from these differences that the results of laboratory studies of noise-induced sleep disturbance could not be generalized to predict the ability of familiar noises to disturb sleep in fully habituated residential populations.
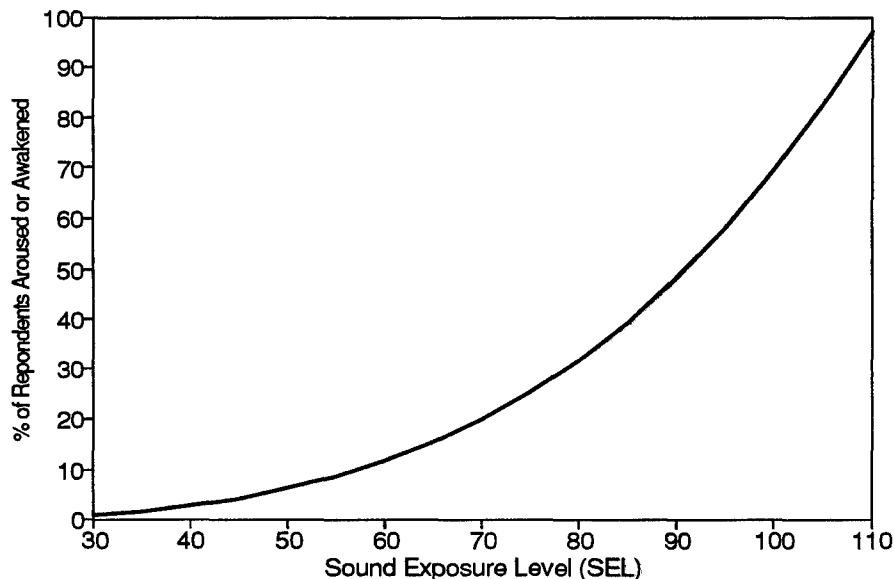
Figure 6   *Dosage-response curve adopted by Federal Interagency Committee on Noise (FICON). (Sound Exposure Level values are measured indoors.)*

Not all of the field studies reviewed by Pearsons *et al.* were conducted at sites similar to those of concern to Air Force environmental planners, nor with noise sources closely resembling aircraft overflights. Ollerhead, Jones, Cadoux, Woodley, Atkinson, Horne, Pankhurst, Reyner, Hume, Van, Watson, Diamond, Egger, Holmes, and McKean (1992) reported findings of a large scale field study of the disturbance of sleep by aircraft noise after completion of the review of Pearsons *et al.* As shown in Figure 8, the data reported by Ollerhead *et al.* closely resemble those of the other field

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studies reviewed by Pearsons et al.[1] The similarity of the findings of these six field studies strongly suggests that laboratory findings on noise-induced sleep disturbance do not accurately predict sleep interference in communities.

3.2 Nature of Dosage-Response Relationships for Prediction of Effects of Community Noise Exposure

The first step in developing a dosage-response relationship for complex phenomena such as community annoyance or sleep disturbance is selection of predictor (independent) and predicted (dependent) variables. Ideally, this selection would be based on thorough, theory-based understanding of the phenomena of interest. In practice, since regulatory and other policy-related uses of dosage-response relationships cannot await development of complete understanding, predictor and predicted variables are customarily chosen on other grounds. The dependent variable which has proved most robust and generally useful for predicting noise-induced annoyance for environmental analysis purposes is the prevalence of a consequential degree of self-reported annoyance.

The independent variable which has proved most useful for similar purposes has been a cumulative measure of long term noise exposure, the Day-Night Average Sound Level (DNL). In many urban noise environments, DNL values are controlled not by individual noise events produced by a small number of sources, but rather by contributions of many noise sources of varying level. The fundamental assumption linking predictor and predicted variables is the so-called "equal energy hypothesis". The equal energy hypothesis holds that the number, level and duration of noise events are fully interchangeable determinants of annoyance as long as their product (energy summation) remains constant. The equal energy hypothesis is important not only because it provides a plausible rationale for a causal relationship between noise exposure and community response, but also because it supports a definition of noise dose that lends itself to tractable manipulation and mathematical modeling. The hypothesis is so essential for noise source modeling that it would be an oversight to neglect its potential applicability to prediction of noise-induced sleep disturbance.

3.3 Differences Between Dosage-Response Relationships for Annoyance and Sleep Disturbance

Several attempts have been made to predict sleep disturbance from noise exposure for purposes of environmental analysis and planning. A set of contrasts in the following subsections points out differences between dosage-response relationships intended to predict sleep disturbance and those intended to predict prevalence of annoyance.

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[1] This comparison is based on the assumption that 40% of the arousals reported by Ollerhead et al. (1992) represent aircraft noise-induced awakenings, and that indoor noise levels are approximately 20 dB lower than those reported by Ollerhead et al. for outdoor measurements.

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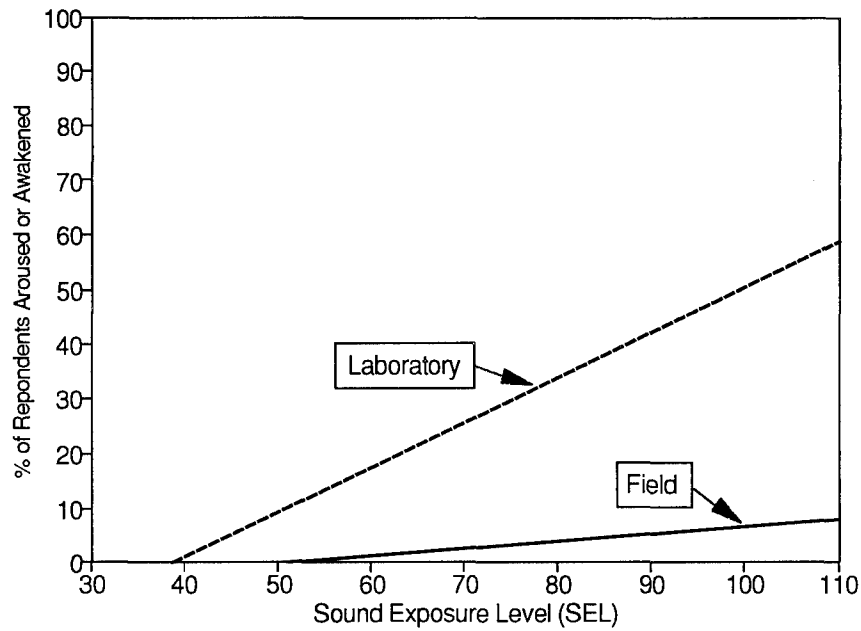
Figure 7   *Summary of dosage-response relationships developed by Pearsons et al. (1989) between awakenings or arousals and indoor sound exposure levels.*

3.3.1   Limitations of laboratory and field observations

A basic difference between dosage-response relationships for predicting prevalence of annoyance and for predicting sleep disturbance is the nature of the data from which the relationships have been inferred. No observations of the responses of individuals to controlled exposures to noises (such as annoyance judgments solicited under laboratory conditions) are included in widely accepted dosage-response relationships for the prevalence of annoyance in communities. Instead, all of the information that is summarized by dosage-response relationships for predicting annoyance is derived from observational (field) studies using survey techniques.

In contrast, the better known dosage-response relationships for predicting sleep disturbance from noise exposure (including those of Lukas, 1975, Griefahn, 1980, and FICON, 1992) have been based principally on observations of sleep disturbance made under controlled laboratory conditions. No explicit rationale supports extrapolation of laboratory findings about sleep disturbance to community settings. Lukas (1975) for one, notes that it is "unknown" whether sleep disturbance measured electrophysiologically in the laboratory can be generalized to field conditions.

Relationships such as that derived by Lukas (1975) account for considerably less variance than dosage-response relationships for annoyance. The range of levels of individual noise intrusions associated with the same amount of sleep disturbance is enormous; characterization of noise exposure via single-event noise metrics is awkward for many purposes; and the compound nature of the

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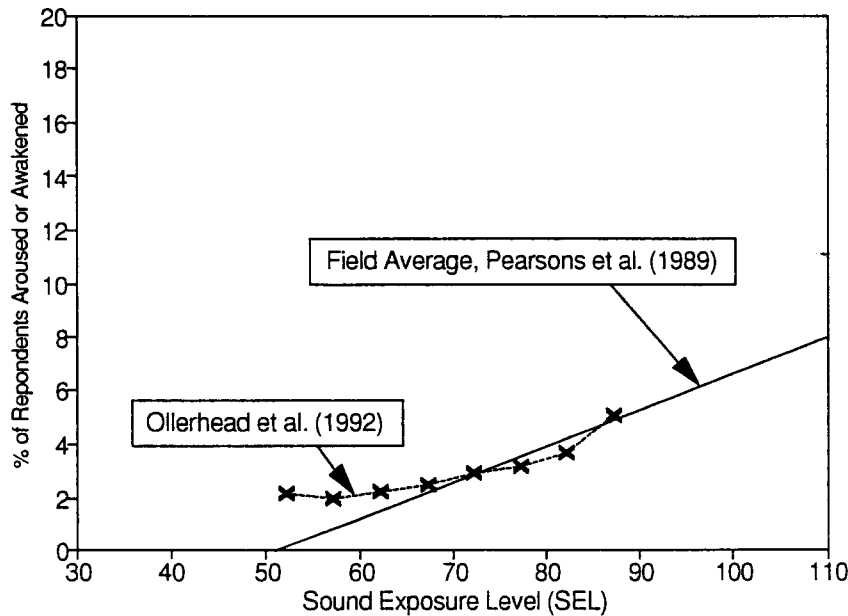
Figure 8 *Comparison of findings of Ollerhead et al. (1992) with regression equation for field study findings developed by Pearsons et al. (1989). (Note exaggeration of vertical scale.)*

predicted variable (percent of test participants exhibiting sleep state change **or** awakening) is difficult to interpret for environmental analysis purposes. Definitions of awakening and sleep disturbance that can be difficult to interpret for environmental planning purposes remain common. For example, Ollerhead *et al.* (1992) define "arousal" as "...the onset of sleep disturbance as measured by an actimeter..."; "awakening" as "... at least 15 seconds of 'wakefulness' **or** 10 seconds of 'movement time' in the EEG record"; and "(sleep) disturbance" as "... both awakenings and actimetrically determined arousals...." Ollerhead et al. note that the latter term includes "events ... such as EEG-awakenings which, *if experienced often enough*, could have longer-term consequences." [emphasis added].

Sleep disturbance in laboratory studies is generally inferred from limited numbers of presentations of test signals at carefully controlled levels. Predictions of sleep disturbance derived from studies which do not consider the number of times that noise intrusions at given levels do *not* disturb sleep may overestimate the ability of noise intrusions to disturb sleep. Unless adjustments are made for frequency of presentation of signals at different levels, it can be difficult to distinguish between the "Percent of subjects aroused or awakened" by noise intrusions which almost always arouse or awaken and by noise intrusions which arouse or awaken only rarely.

Dosage-response relationships inferred from observations made in certain study designs can be even more difficult to interpret. For example, in controlled exposure studies employing the method of limits (in which signals of increasing level are presented until an effect is observed), the occurrence of sleep disturbance at a given signal presentation level is conditional upon an absence of disturbance at a sequence of prior (lower) presentation levels. Since community noise intrusions do not occur in predictable sequences of ascending level, it is unclear how to adjust the data of such studies to predict the independent effects of individual noise intrusions at random levels.

3.3.2   Conventional locus of noise measurement

The predictor variable for the best known dosage-response relationships for predicting noise-induced annoyance in residential settings (e.g., Schultz, 1978; FICON, 1992) is a place-oriented measure of long term outdoor noise exposure. In contrast, the predictor variables for all of the better known dosage-response relationships for noise-induced sleep disturbance are measures of indoor noise exposure in sleeping quarters.

Indoor and outdoor measures of residential noise exposure differ not simply by the sound attenuation of a structure, but also by the origin of noise exposure. Outdoor noise events of high level may produce similar noise exposure outside many residences in a neighborhood. The indoor noise exposure of residences may not be controlled by outdoor sources at times when people are home, however (Schultz, 1982, pp. 261 *et seq.*). The numbers and levels of noise events inside residences may be controlled by discretionary sources such as home appliances, power tools, electronic entertainment, and other sounds of family activities. All of these sounds of indoor origin may potentially disturb sleep, but are unlikely to affect noise levels recorded outdoors.

The difference in locus of noise measurement for predictive relationships for annoyance and sleep disturbance is related to historical differences between goals of laboratory and field study. The customary objective of most laboratory studies of noise-induced sleep disturbance has been to increase understanding of the manner in which noise disturbs sleep. The objective of field study has more often been collection of information useful for more limited regulatory or policy-related purposes. The former objective is more fully satisfied by at-ear noise measurements, while the latter goal can be satisfied by outdoor measurements.

3.3.3   Selective definition of noise exposure

Another important difference between predictive relationships for annoyance and sleep disturbance is the restrictive nature of the noise exposure measurements from which the latter relationships are constructed. Predictions of the annoyance of community noise are based on fully inclusive measurements: outdoor noise energy from **any** source, of **any** duration, level, and time of occurrence contributes to the value of the predictor variable.

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In contrast, most predictions of the ability of noise intrusions to disturb sleep are based on event-specific measurements, rather than on the entire noise environment in sleeping quarters. These events are typically defined rather selectively. In the case of laboratory studies, an association between noise and sleep disturbance is generally sought only for particular events of interest to the experimenter. In the case of field studies, associations are generally sought only between sleep disturbance and noise events defined by more or less arbitrary rules.

Ollerhead *et al.* (1992), for example, analyzed only the relationship between sleep disturbance and noise events characterized by outdoor SEL values in excess of 60 dB which also coincided with confirmed times of known aircraft overflights. In other words, potential sleep disturbance associated with noise events of non-aircraft origin, of any magnitude, whether produced inside or outside residences, was excluded (by design) from analysis. This exclusion is consistent with a strong focus on the potential sleep disturbance of noise produced by aircraft alone.

3.3.4   Shapes of dosage-response relationships

Dosage-response relationships used to predict annoyance are generally curvilinear or sigmoidal. They have ranged from arbitrary polynomial fits (e.g., Schultz, 1978), to nonlinear least squares fits (e.g., Fidell, Barber and Schultz, 1991), to exponential fits (e.g., FICON, 1992), to fits derived from theoretical models (e.g., Green and Fidell, 1990). S-shaped dosage-response relationships are often convenient for describing effects quantified by dichotomous measures (e.g., awakening vs. non-awakening) when such relationships are asymptotic to values in the vicinity of 0% and 100%. To the extent that such relationships resemble cumulative Gaussian distributions, they are generally well fit through logit or probit (normal probability) transformation of response percentages prior to linear regression analysis. However, since probit and logit transforms are undefined in the region of 0%, such transformations may complicate analyses of data sets with many cases characterized by lack of response (awakenings).

In contrast, dosage-response relationships reported in the sleep literature are generally linear. Pearsons *et al.* (1989) attempted to improve linear regressions of noise metrics on sleep disturbance data via probit transformation, but found no gain in predictability. Several factors may have contributed to this lack of improvement, including the relative paucity of data points when those characterized by lack of response were eliminated, restricted ranges of some data sets, and errors of approximations in converting data from diverse studies into common units.

3.4 Common Metrics of Noise Exposure in Sleep Studies

Community noise exposure may be characterized for purposes of predicting sleep disturbance by a number of single event and cumulative noise metrics, most of which are highly correlated with one another. Lukas (1977) evaluated four noise metrics in developing a dosage-effect relationship between noise and sleep disturbance in his review of the effects of noise on sleep: (1) maximum A-

level, (2) "effective" (duration corrected) A-level, (3) Effective Perceived Noise Level (EPNL), and (4) Single Event Noise Exposure Level.[2] Lukas preferred EPNL as the independent variable for his dosage-response relationship. Griefahn (1980) subsequently derived a dosage-effect relationship based on a single event noise metric (maximum A-level) as the independent variable. Pearsons *et al.* developed separate relationships for both maximum A-level and Sound Exposure Level (SEL).

At least in principle, other metrics of aircraft noise could also serve as predictor variables for dosage-response relationships. For individual events, these include Perceived Noise Level (PNL), SEL, and C-weighted level. Measures of groups of noise events and of an entire night's exposure, including (1) Equivalent Noise Level (L_{eq}), (2) Day-Night Average Level (DNL), and (3) Cumulative Distribution Levels (centiles) ($L_{\%}$) are also potential predictor variables. A metric that takes into consideration the relationship between noise events and ambient levels might also serve as a useful predictor variable.

Noise exposure was measured in the present study in such a way that a suite of A-weighted individual event and cumulative metrics could be calculated. Since many of these metrics are highly correlated, only a few were considered in the present analyses. Absent significant differences in the predictive value of noise metrics, the most parsimonious, conveniently manipulated, and economically measured one(s) would be preferred for most purposes.

3.4.1 Definition of noise events

Noise exposure associated with sleep disturbance in a field study cannot be identified *a priori* because it is not under experimental control. A clear definition of noise events is needed to compensate for this lack of control. A common procedure for defining noise events in an observational study is to restrict attention to events which exceed a site-specific A-weighted threshold, persist for a minimum duration, and subsequently fall to a level several dB below the initial threshold. Site-specific tuning of such definitions, although unavoidably arbitrary, can nonetheless aid in characterizing both aircraft overflights and most other non-transient, relatively high level noise events of non-aircraft origin.

3.4.2 Definition of noise epochs

An alternative approach to characterizing noise exposure which may be associated with sleep disturbance in an observational study is to construct a continuous time series of noise measurements that can be divided into consecutive epochs of specified duration. These epochs can be scrutinized in a post hoc fashion for association between noise levels and sleep disturbance. Definitions of such epoch-based measurements of noise exposure can be somewhat less arbitrary and site-specific than

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[2] Two of these metrics, "duration corrected A-Level" and "Single Event Noise Exposure Level", differ only by a constant.

those of event-based measurements. Epoch-based analyses can also permit examination of a broader range of hypotheses about the association between noise exposure and sleep disturbance than event-based analyses. Appendix C contains additional discussion of this issue.

3.5 Common Metrics of Sleep Disturbance

Sleep disturbance may be measured in a number of ways of varying detail, cost, and appropriateness for different purposes, as described below.

3.5.1 Electroencephalographic measures

Electroencephalographic (EEG) techniques, which provide the greatest detail about sleep quality, have been employed for many years in clinical and laboratory applications. The familiar classification of sleep into cycles of lighter and deeper "stages", defined on the basis of relative amounts of cortical activity in different frequency ranges, is a product of EEG measurements. Successful EEG measurements require specialized training and equipment, are susceptible to artifacts of electrode placement, movement and muscular activity, and (since they require attachment of electrodes to the head) are highly intrusive.

EEG measurements are thus most appropriate for studies intended to produce large amounts of highly detailed information about the sleep of relatively small numbers of test participants for short periods of time under controlled conditions. Costs of acquiring, processing, and interpreting EEG data are generally prohibitive for large scale, long term field studies. Since many questions about the policy implications of physiological states distinguishable by EEG techniques remain unresolved, EEG data can also be difficult to interpret for non-clinical purposes such as environmental planning.

3.5.2 Self-report

The advantages and disadvantages of self-report measures of sleep disturbance complement those of EEG measurements: although inexpensive to acquire, self-reports yield relatively little detailed information. Self-reports can be immediate or delayed, and may range from long term estimates in social surveys administered to large numbers of people ("About how often do you wake up at night due to ___ noise?") to shorter-term questionnaires administered to individuals upon arising ("How many times did you wake up last night?"). Self-reports have obvious advantages of cost and ease of measurement, as well as equally obvious shortcomings of interpretation due to their susceptibility to effects of intervening variables such as memory and reporting bias.

3.5.3 Behavioral measures

Several sorts of behavioral indications of sleep disturbance are intermediate in utility and detail between EEG and self-report measures. For example, since gross body movements cease only during periods of deep sleep (Ollerhead *et al.*, 1992), sleep disturbance may be measured by a wrist-worn

recording accelerometer (an "actimeter"). Ollerhead *et al.* have made considerable efforts to relate motility to EEG activity. These efforts have not yet been fully successful in reliably distinguishing "arousals" (shifts from deeper to lighter sleep states) from "awakening" (departure from an intuitively meaningful definition of sleep). Ollerhead et al. (1992) believe that about 40% of arousals inferred from highly processed motility data represent awakenings, but despite careful analysis of actimetric data, are unable to distinguish arousals from awakenings on an episode-by-episode basis.

Behavioral indications of sleep disturbance other than motility have also been adopted in prior research. Perhaps the most straightforward is awakening confirmed by a button press (*cf.* Horonjeff, Fidell, Teffeteller, and Green, 1982). Although behaviorally-confirmed awakening does not provide fine detail about sleep state changes, disturbance so defined is relatively unambiguous, lends itself to straightforward interpretation, and can be cost-effectively measured with good temporal resolution under field conditions in a large scale study. The possibility exists that this measure is subject to reactivity, especially biases due to unfamiliarity in the early stages of data collection and waning motivation in the later stages. This source of bias can be assessed by examining overall response rates associated with time in the study.

3.6 Role of Nonacoustic Factors in Sleep Disturbance

Pearsons *et al.* (1989) and others have found that a number of factors other than noise level affect awakenings and changes in sleep state. These other factors include gender, noise source (jet aircraft, sonic booms, traffic or other), background noise, and the length of time subjects had participated in the study. Studies other than that of Pearsons *et al.* have reported effects of age on sleep patterns. The differences between field and laboratory results suggest adaptation to noise exposure through long term familiarity. The current study offered opportunities for assessing some of these factors, as well as others not extensively analyzed in prior studies. The latter include spontaneous awakening rates as measures of individual differences in susceptibility to sleep disturbance.

3.7 Issues Affecting Modeling of Relationship between Noise Exposure and Sleep Disturbance

It may suffice for regulatory purposes to predict noise-induced sleep disturbance solely from outdoor noise measurements. This approach does not necessarily support development of a defensible dosage-response relationship for all environmental assessment purposes, however. A fuller understanding of the manner in which noise exposure disturbs sleep requires, for example, that the characteristics of two types of noise events be distinguished if possible: those which do and those which do not disturb sleep. Clearly, noises of outdoor origin are not the only factors that can disturb sleep. Sleep may also be disturbed by indoor noises, and may be affected by familiarity with noise sources and other nonacoustic factors such as health status, daily activity levels, prior nights' sleep experiences, and other personal and environmental conditions.

Explicit discussion of the rationale for selecting noise metrics for dosage-response relationships between noise exposure and sleep disturbance is rare. Researchers' choices of independent and dependent variables for dosage-response relationships sometimes suggest tacit models, however. For example, Lukas's (1975) synthesis is based tacitly on the belief that it is the "effective" (that is, duration-adjusted, or 10 log (duration)) Perceived Noise Level (EPNL) of individual noise intrusions that causes sleep disturbance, whether measured by awakening or by change in electroencephalographic sleep stage.

A researcher's choice of EPNL as a predictor variable also implies:

- that the maximum level of a sound is not a direct determinant of its ability to awaken people;

- that the duration of a noise event is just as important a determinant of its ability to disturb sleep as its level;

- that the Perceived Noise Level of a sound is a more useful predictor of sleep disturbance than the A-weighted level of a sound; and

- that the total number of noise intrusions, the rate of occurrence of noise intrusions, the time of occurrence of noise intrusions, the cumulative levels of multiple noise events, the ambient noise environment of sleeping quarters, and similar acoustic variables may be ignored for predictive purposes.

Other researchers have expressed conflicting views about the sleep disturbing properties of noise. Griefahn (1980), for example, suggests that it is the maximum A-weighted sound level of single noise events, not their duration-adjusted values, that causes sleep disturbance. This position implies that numbers and durations of noise intrusions are of negligible importance as predictors of sleep disturbance. Ohrstrom and Rylander (1990) suggest that the numbers and rates of occurrence of noise intrusions rather than their maximum levels and/or durations are more probable determinants of sleep disturbance.

Single event metrics are awkward for environmental assessment, policy, planning, and regulatory purposes, since they do not lend themselves readily to predicting the effects of multiple noise intrusions. They are also less readily manipulated and interpreted than long term, integrated-energy metrics.

So little is quantitatively known about sleep disturbance in field settings that many hypotheses about the sleep disturbing properties of noise remain plausible. For example, it may be that the levels or durations of noise intrusions do not determine sleep disturbance so much as their audibility (i.e., their levels with respect to the ambient noise environment of the bedroom). Likewise, the ability of a noise to disturb sleep may be affected by the familiarity or other properties of noise, such as impulsiveness, temporal variability, origin (inside or outside sleeping quarters), etc.

It is also possible that sleep disturbance is not strongly related to acoustic characteristics of individual noise events. Instead, some total number of noise intrusions, or perhaps some rate of noise intrusions, may have to occur before sleep is disturbed. The nth event in a series of noise intrusions occurring within some time period at levels greater than a threshold might be the proximal cause of an awakening. Alternatively, an entire pattern of noise intrusions may be important in causing sleep disturbance rather than individual events.

Finally, nonacoustic factors such as the meaning of noise intrusions, age, gender and other individual differences may be more closely associated with sleep disturbance than acoustic factors. Habituation may be such a strong determinant of the effect of noise on sleep that noises that awaken people in unfamiliar environments, such as settings for laboratory studies, may cause little or no sleep disturbance after they become familiar.

3.8 Nature and Need for Control Sites

It is unclear what (if any) control conditions are appropriate for field studies of noise-induced sleep disturbance, in part because most prior studies were conducted under laboratory conditions. In an early study of sleep electrophysiology in the home, Pearsons, Bennett, Fidell, Friedmann and Globus (1974) noted that sleep patterns of all test participants, both those living near a major airport and those living elsewhere in the same metropolitan area, did not conform closely to the nominal patterns expected on the basis of laboratory sleep measurements. A within-subjects study design, in which test participants serve as their own controls under differing noise exposure conditions, is perhaps the most that can be hoped for under such conditions.

Further, no field study to date has made any pretense that its test participants are representative of any particular population. Thus, the issue of appropriate control sites is not so much one of experimental design as of the nature of the inferences to be drawn from a study. If one were interested primarily in determining whether noise-induced sleep interference was strongly related to the source of noise exposure, then one might consider sites with relatively high, non-aircraft noise exposure as control sites. If, however, one were more interested in the role of outdoor noise exposure *per se* in sleep disturbance, then one might consider sites with very low outdoor noise exposure as control sites. It is also conceivable that sites with similar outdoor but different indoor noise exposures could be considered as control sites for some purposes.

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4 METHOD

This Chapter describes procedures used to develop instrumentation, select sites, collect and reduce sleep disturbance data, and measure noise exposure.

4.1 Pilot Study

A pilot study was conducted prior to the start of data collection to verify the adequacy of instrumentation, data collection, and analysis procedures. Instrumentation configuration, installation, operating and servicing procedures were tested and refined, as were interactions of test participants with the instrumentation. The wording and presentation order of questionnaire items were optimized for minimal effort on the part of test participants, and formal instructions were prepared and tested for clarity. No data collected during the pilot study are included in the analyses reported in Chapter 5.

4.2 Site Selection

Sites near military and civil airports were selected according to the following criteria:

- sufficient aircraft operations to provide adequate opportunities for observing awakenings to warrant the expense of data collection;
- presence of a sufficient number of residences to yield at least 25 test participants;
- sufficient variability in overflight noise levels to observe the effects of a range of overflight exposure on sleep disturbance; and
- sufficient predictability and stability of exposure conditions over the intended observation period to warrant the expense of data collection.

Residential areas near Castle Air Force Base and Los Angeles International Airport were selected as test sites. A number of suburban and urban sites lacking appreciable nighttime aircraft noise were selected as control sites.

4.2.1 Castle Air Force Base

Castle Air Force Base's 93rd Bomb Wing is a U.S. Air Force Air Combat Command unit located 7 miles north of the city of Merced in California's San Joaquin Valley. The wing operates approximately 25 B-52 aircraft which fly more than 13,000 hours per year, and 30 KC-135A and 15 KC-135R which fly more than 23,000 hours yearly. These operations include touch-and-go training flights on week nights. No nighttime training operations are conducted on weekend nights. Residences located as shown in Figure 9 near the ends of the main runway have been exposed for several decades to very high noise levels from military jet takeoffs and landings during both daytime and nighttime hours. Figure 9 includes noise contours to provide an indication of the average outdoor noise levels in the test area.
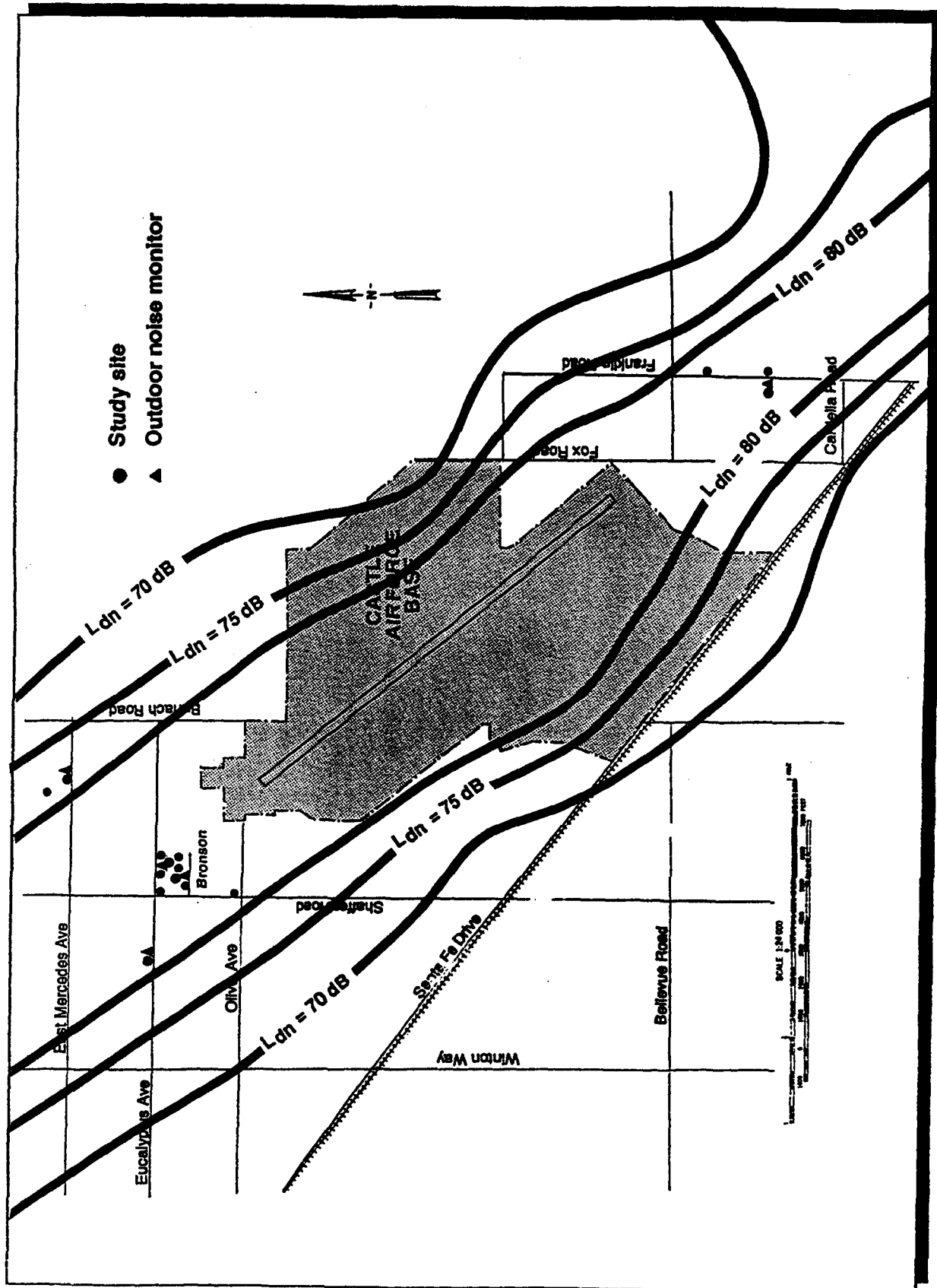
Figure 9 *Geographic relationship between Castle Air Force Base and data collection sites. (Source: 93rd Bomb Wing, Public Affairs Office, Castle AFB CA)*

4.2.2   Los Angeles International Airport

Los Angeles International Airport (LAX), situated on the coast of Santa Monica Bay, conducts an average of more than 1800 flight operations a day on two pairs of east-west runways. A residential area of single family detached homes located as shown in Figure 10 has long experienced both approach and departure noise during nighttime hours. Homes with lines of sight to the runways are also exposed to thrust reverser and ground runup noise. Noise contours shown in Figure 10 provide an indication of the average outdoor noise levels in terms of CNEL (approximately equal to DNL) in the test area.

4.2.3   Control sites

Twelve residences in suburban Los Angeles with negligible nighttime aircraft noise exposure were selected as control sites. Two of these residences were located adjacent to major freeways, three were located close to busy streets, and the remaining residences were in neighborhoods with lesser noise exposure. These sites were purposively selected for a range of outdoor noise exposures which overlapped the range of levels expected at LAX.

4.3 Test Participants

Test participants were recruited through mailings to residences within address ranges selected after site visits. Address lists were assembled from direct observation of street addresses, reverse telephone directories, and information purchased from commercial re-sellers of public property records. The initial mailing included letters describing the study and a return form for those interested in participation. Follow up of returned indications of interest was accomplished via telephone. The highly localized spatial distribution of aircraft noise exposure, presumed self-selection biases of neighborhood residence, and relatively small numbers of eligible households and test participants precluded any efforts to obtain a random sample.

An honorarium of $100 was offered for up to four weeks' participation in the study. Site visits were made to inspect residences to verify their noise exposure and overall suitability, make an informal determination of potential test participants' hearing ability, install equipment, train test participants, and schedule equipment maintenance visits. An instruction booklet was provided to prospective test participants prior to equipment installation. Use of the response recording instrumentation was explained and demonstrated at the time of initial installation, and re-iterated during service visits. A toll-free telephone number was given to test participants to encourage them to request clarification of procedures at any time. Appendix B contains further detail about recruitment procedures, instructions to test participants, and questionnaires.

All willing residents at Castle AFB (28 people in 15 households) took part in the study. At LAX, 35 people in 18 households were selected as test participants from a total of 66 returns

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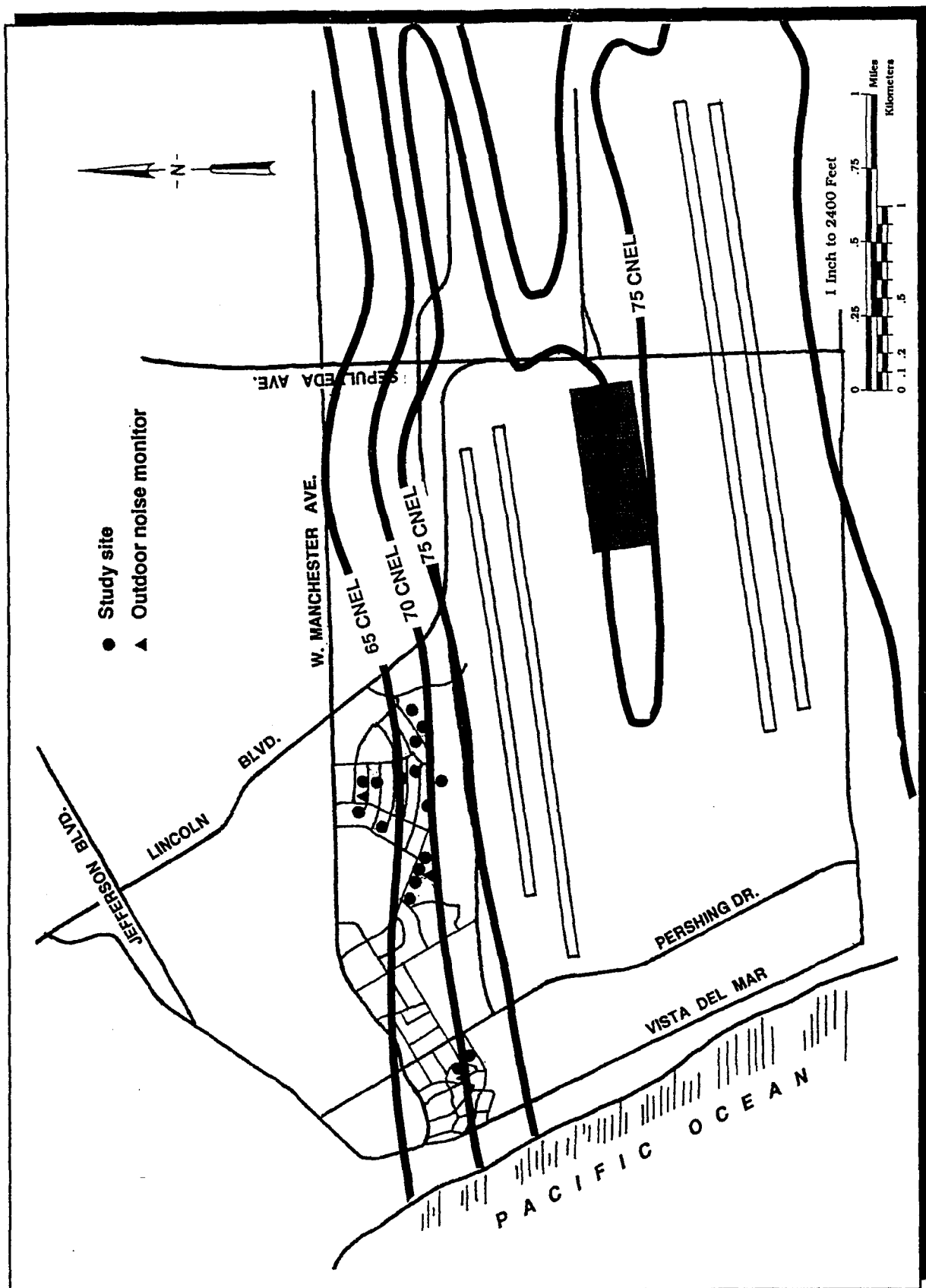
Figure 10 *Geographic relationship between Los Angeles International Airport and data collection sites. (Source: Los Angeles International Airport, Noise Abatement Office, Los Angeles CA)*

indicating interest in the study. Selection of households at LAX was made on the basis of the following overall requirements and preferences:

- approximately equal numbers of men and women;
- at least two people participating in each household;
- a range of ages, from young adult couples to the elderly;
- neighborhood residence for at least 3 months and good general health;
- households in which occupants of shared sleeping quarters were likely to be present for all test nights; and
- households with differing ambient noise environments in sleeping quarters.

An additional 23 people in 12 households that were not exposed to nighttime aircraft noise also participated at control sites.

4.4 Noise Measurements

Noise measurement instrumentation was assembled to support automated data capture, processing and analysis of large amounts of noise exposure information. Figure 11 diagrams the instrumentation used to collect noise exposure information. This equipment preserved time synchronization among data streams for time series of A-weighted sound pressure measurements recorded indoors and awakening responses from test participants' hand switches.

Indoor noise measurements were made in all test participants' sleeping quarters with Larson-Davis 820 noise monitors. Data capture by these monitors were downloaded approximately once per week, in conjunction with visits to test participants' homes for other purposes. Outdoor noise measurements were made with Larson-Davis 870 noise monitors in the vicinity of 5 residences near Castle Air Force Base and 4 residences near LAX.

Several two-channel, wide-band noise recordings were made with a calibrated videocassette recorder at one residence at Castle AFB and one residence at LAX[3]. This instrumentation permitted simultaneous broadband recordings of indoor and outdoor aircraft noise levels from the microphones employed for A-level measures. A time track permitted synchronization with A-weighted measurements made by indoor and outdoor noise monitors at these two sites.

Indoor noise measurements were made from 10:00 PM to 8:00 AM with microphones placed inside test participants' bedrooms. L_{eq} values were recorded every 2 seconds throughout each night. Half-second time histories of noise "events" were also recorded. A noise event was defined as a sequence of noise levels that exceeded a threshold level for at least 2 seconds, and did not drop more than 2 dB below the threshold at any time. The threshold was set on a site-specific basis to maximize

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[3] No analyses of these spectral data are described in this report.
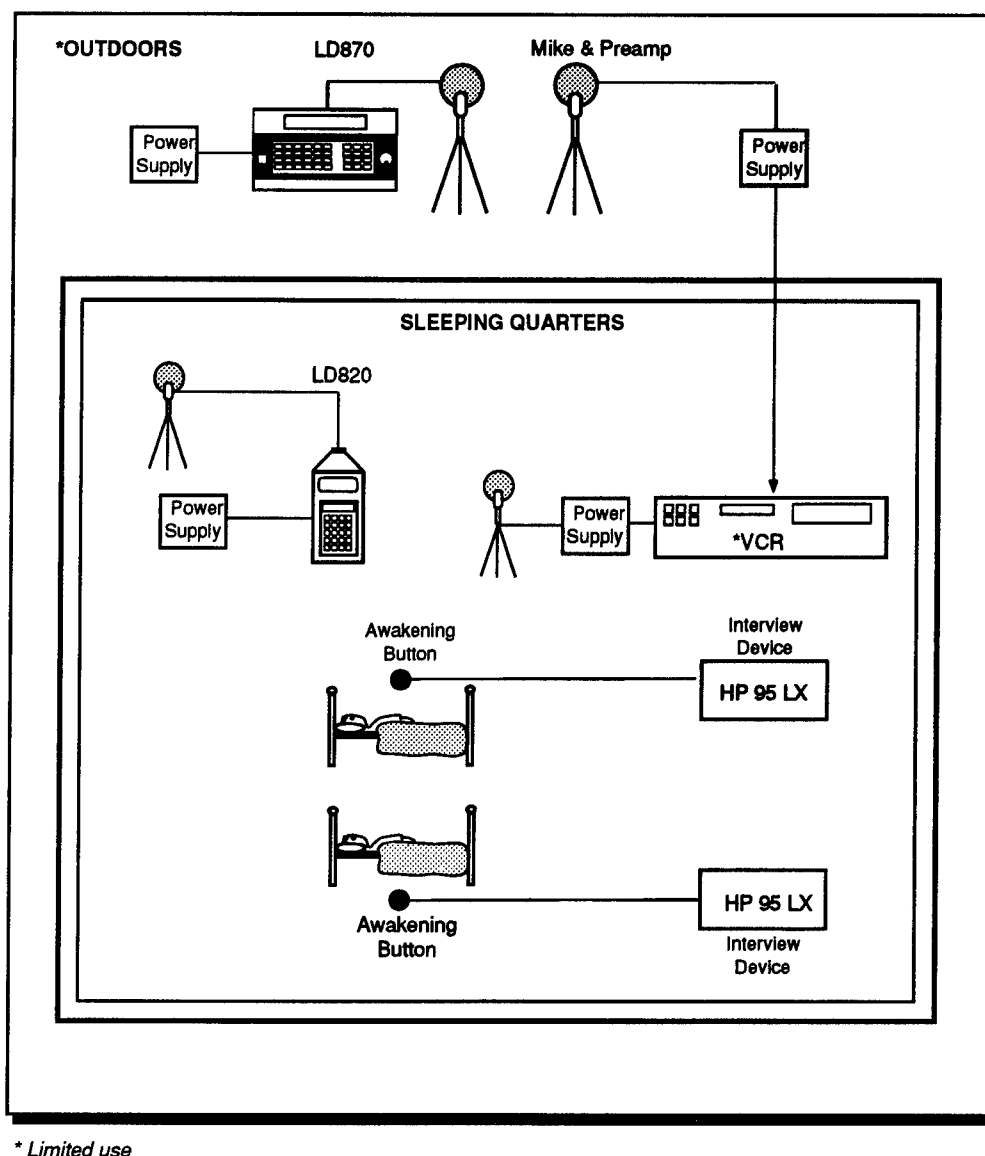
Figure 11 *Schematic diagram of field instrumentation.*

collection of noise intrusions (primarily aircraft) in the presence of indoor ambient noise, without exhausting the storage capacity of the noise monitors too rapidly. Indoor thresholds were set at 70 dBA at Castle Air Fore Base, and 60 dBA at LAX and control sites. The practical effect of the 10 dB difference among sites in threshold levels was negligible for high level noise intrusions such as aircraft overflights at Castle Air Force Base.

4.5 Response Measurements

A palmtop computer (HP-95LX) was provided to each test participant to administer the evening and morning questionnaires. A pushbutton attached at the end of a short cable to the device served as the behavioral confirmation of awakening during the night.

4.6 Study Design and Analysis Plan

This section describes the study design, hypotheses, and data analysis.

4.6.1 Independent Variables (Noise Measures)

Three types of measures of noise levels in sleeping quarters were considered: (1) metrics describing levels of individual noise events, (2) metrics describing noise levels during specific analysis epochs, and (3) metrics describing cumulative, long term measures of noise. Table 1 shows the metrics for each type of noise measure. Metrics reflecting peak levels (e.g., maximum A-level), average values (e.g., SEL or L_{eq}), and A-weighted Signal-to-Noise (A-weighted S/N) ratios were among those measures computed. A-weighted Signal-to-Noise values were calculated for individual noise events based on A-weighted measures of signals (i.e., events) and an rms calculation of the 25 sec preceding the signal as a measure of ambient levels.

Table 1 *Noise Metrics Considered.*

Type of Analysis	Noise Measure
Individual Events	Sound Exposure Level (SEL) Maximum A-level A-weighted S/N L_{eq}
Time Epochs	L_{eq}
Cumulative (Entire Night)	Maximum L_{eq} L_{eq} for whole night Number of events above criterion level Duration of events above criterion level

4.6.2 Dependent Variables (Response Measures)

A total of nine dependent variables, listed below, were analyzed in this study. These variables were derived from behavioral awakening responses, responses to items presented in morning questionnaire, and calculations based on these quantities.

- number of button pushes (as registered by palmtop computer),
- judgment of overall sleep quality (morning questionnaire),
- feeling of tiredness (morning questionnaire),
- recall of number of awakenings (morning questionnaire),
- recall of time to fall asleep (morning questionnaire),

- length of sleep time (recorded time between first and last button push for the night),
- whether respondent reports being awakened by aircraft noise (morning questionnaire),
- annoyance with aircraft noise exposure (morning questionnaire), and
- report of amount of time awake during the night (morning questionnaire).

4.6.3 Control Variables

Several control variables which could affect sleep disturbance or modify the relationship between noise intrusions and sleep disturbance were employed in data analyses. One set included blocking variables for which separate (parallel) dosage-response analyses were performed. These blocking variables include:

- duration of analysis epoch (1, 2, and 5 minutes) prior to each event; and
- duration following each event (1, 2, and 5 minutes).

A second set of control variables included nonacoustic variables which may contribute to prediction of sleep disturbance. These latter variables are categorized as noise-related, participant-related, time-related, and presleep-related variables. Table 2 displays these variables by type.

Table 2 *Control Variables by Type.*

Type	Control Variables
Noise-related	Ambient level Site (Castle AFB, vs. LAX vs. Control)
Participant-related	Spontaneous awakening rate Household identification Age Gender
Time-related	Minutes since retiring Number of nights in the study Months in residence
Presleep-related	Feeling of tiredness prior day Alcohol prior evening Medication prior evening

- Noise-related control variables included ambient noise level and site.
- Participant-related control variables included spontaneous awakening rates as an indicator of individual differences in soundness of sleep, age, and gender. Spontaneous activity was measured as rates of button pushing in the absence of noise events. Household identification served to control for individual differences inherent in repeated measures from the same participant.

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- Time-related variables included time since retiring, number of nights that the respondent has participated in the study, and time in residence.
- Presleep-related variables assess the participants' state the previous day and just prior to retiring: (1) self-assessed tiredness the prior day, (2) alcohol consumption and (3) medications taken the prior evening. These three variables were assessed via the prior evening's interview.

4.6.4 Hypotheses

Three types of hypotheses were of interest: (1) those concerning dosage-response relationships between alternate noise metrics and response measures (*cf.* Sections 4.6.4.1 through 4.6.4.3), (2) those concerning the relationship between control variables, noise, and sleep (*cf.* Section 4.6.4.4), and (3) supplementary hypotheses (*cf.* Section 4.6.4.5).

Since each of the following prioritized dosage-response hypotheses could in principle have been tested with as many as nine dependent variables, nine analyses could have been conducted of each hypothesis. Fifty-one potential dosage-response hypotheses are diagrammed schematically in Figure 12 and Figure 13. Screening of dosage-response hypotheses was pre-planned to avoid inflated Type I error associated with tests of multiple related hypotheses.

4.6.4.1 Hypotheses about individual noise events tested prospectively

The following hypotheses about the sensitivity of sleep to disturbance by individual noise intrusions were considered:

- The probability of occurrence of sleep disturbance within a specified time period after the occurrence of one or more noise intrusions is a monotonically increasing function of the A-weighted equivalent energy (SEL value) of discrete noise intrusions.
- The probability of occurrence of sleep disturbance within a specified time period after the occurrence of one or more noise intrusions is a monotonically increasing function of the maximum A-weighted level of discrete noise intrusions measured indoors.
- The probability of occurrence of sleep disturbance within a specified time period after the occurrence of one or more noise intrusions is a monotonically increasing function of the A-weighted signal-to-noise ratio of the noise intrusion.
- The probability of occurrence of sleep disturbance within a specified time period after the occurrence of one or more noise intrusions is a monotonically increasing function of the A-weighted equivalent level (L_{eq}) of the sleeper's noise environment since retiring.

4.6.4.2 Hypothesis about awakenings tested retrospectively

The following hypothesis about sensitivity of sleep to disturbance by noise during temporal intervals (epochs) was considered:

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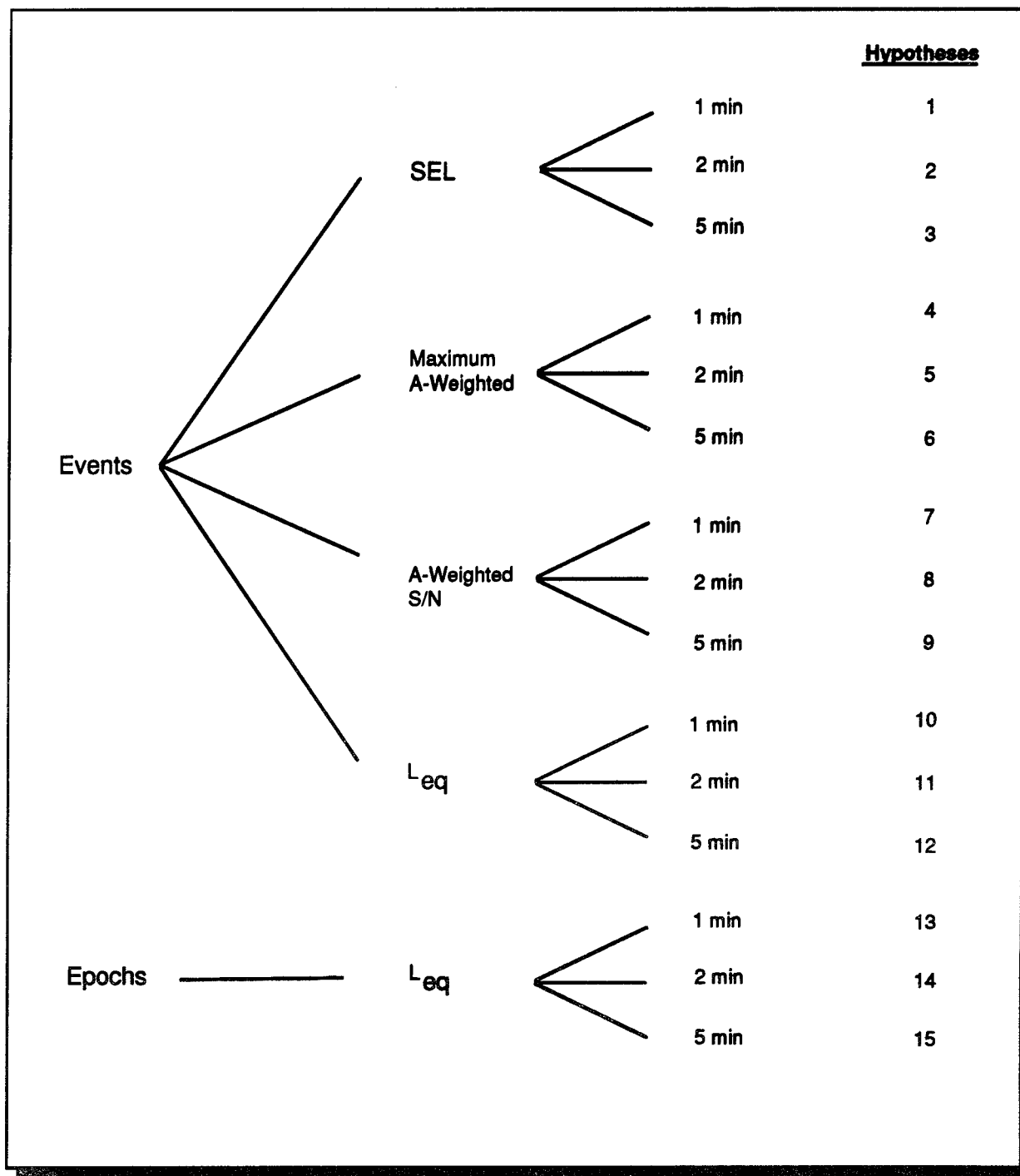
Figure 12   *Schematic diagram of dosage-response hypotheses 1-15.*
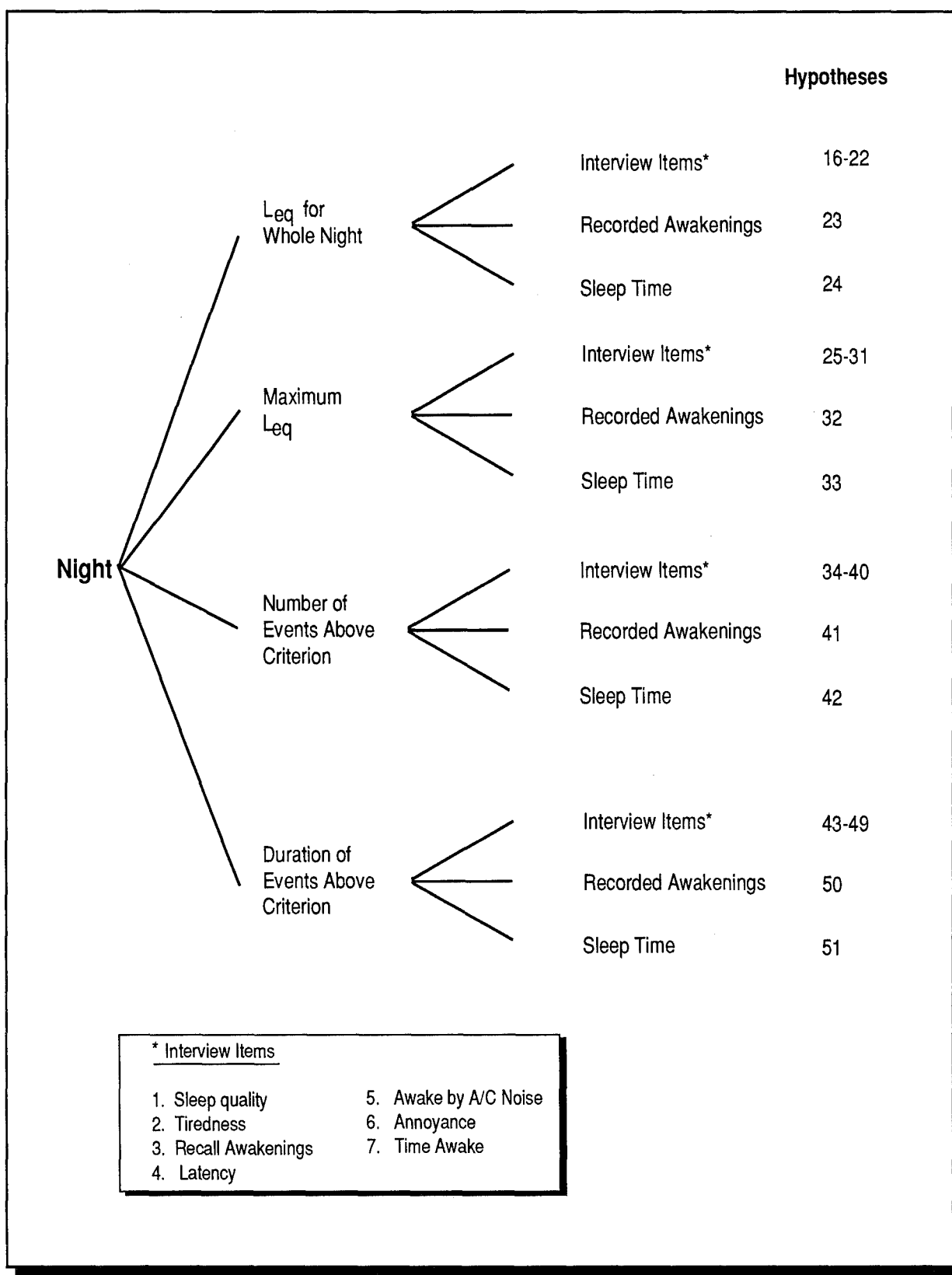
Figure 13   *Schematic diagram of dosage-response hypotheses 16-51.*

- The probability of occurrence of sleep disturbance is a monotonically increasing function of the A-weighted equivalent level (L_{eq}) of noise exposure in a specified time period prior to a behavioral response.

4.6.4.3 Hypotheses about whole night noise exposure

The following hypotheses about sensitivity of sleep to disturbance over a whole night's noise exposure were considered:

- The number of sleep disturbances during a night due to the occurrence of one or more noise intrusions is a monotonically increasing function of the A-weighted equivalent level (L_{eq}) of noise exposures cumulated for the night.
- The number of sleep disturbances during a night due to the occurrence of one or more noise intrusions is a monotonically increasing function of the maximum A-weighted level of noise intrusions as measured indoors.
- The number of sleep disturbances during a night due to the occurrence of one or more noise intrusions is a monotonically increasing function of the number of noise intrusions above a specified level that occur during the night.
- The number of sleep disturbances during a night due to the occurrence of one or more noise intrusions is a monotonically increasing function of the duration of noise intrusions above a specified level that occur during the night.

4.6.4.4 Hypothesis about relationships among noise, control variables, and sleep

- The probability of sleep disturbance is a linear function of noise intrusions. The relationship can be enhanced by considering habituation, susceptibility to sleep disturbance, prior day's experience, and ambient noise.

4.6.4.5 Supplementary hypotheses

The present data set also allows tests of a number of other hypotheses about additional relationships:

- The number of awakenings recalled is a linear function of the number of actual awakenings.
- Annoyance due to noise intrusions is a linear function of behavioral measures of sleep disturbance (awakening and time slept).
- The linear relationship between annoyance and sleep disturbance is strengthened by adding measures of recall of a night's sleep (latency, whether awakened by aircraft noise, and number of awakenings).
- The linear relationship between annoyance and sleep disturbance is strengthened by adding attitudinal responses (sleep quality and tiredness).
- Annoyance due to noise intrusion is a linear function of noise level.
- The maximum A-weighted level is greater for events that awaken residents than for events that fail to disturb sleep.

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4.6.4.6   Screening of hypotheses

Given the large number of plausible dosage-response hypotheses and alternative ways of testing them, a pre-screening was necessary to limit the number of relationships fully investigated. Section 4.6.5 describes the screening procedure followed. Results of the screening are described in Section 5.4.

4.6.5   Data Analysis Plan

This study may be viewed as a repeated measures design in which all test participants experience all levels of major independent variables. In other words, all test participants were exposed to a range of noise levels over a series of nights. Although test participants were paired within households, they differed in covariates such as age, gender, and susceptibility to sleep disturbance.

The sequence of conduct of analyses is shown in Figure 14. Screening analyses determined the specific variables used in subsequent analyses. Further planned analyses included derivation of dosage-response relationships, multiple regression analysis, and supplementary correlations. Additional *post hoc* hypotheses were formulated on the basis of findings in the planned analyses. These were conducted with appropriate adjustments for inflation of Type I error rate (Tabachnick & Fidell, 1989).
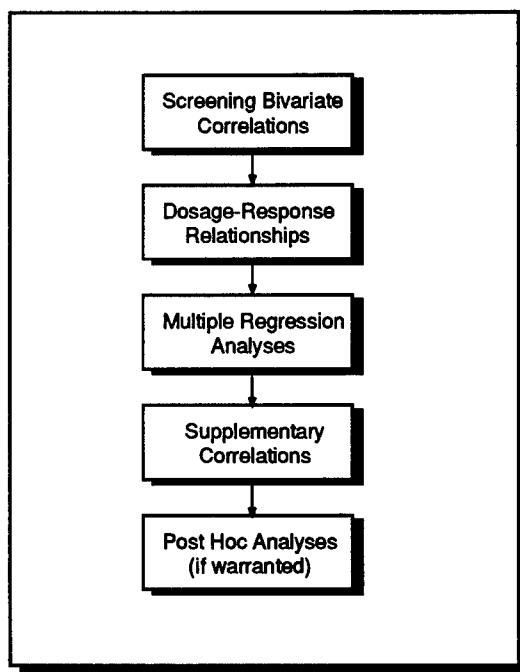
Figure 14   *Preplanned sequence of data analyses.*

Preliminary correlational analyses were conducted to determine the dosage-response relationship(s) which supported the most parsimonious prediction of sleep disturbance from noise

exposure. The dependent variable for analyses of discrete noise events and epochs was probability of awakening. The dependent variables for analyses of whole nights were the average number of awakenings, level of tiredness, etc.

The linear correlation between actual noise level and sleep disturbance was calculated for each dosage-response relationship to be assessed. Correlations that were reliably different from zero were identified. Inferential tests (Fisher's z-transform for the difference between two correlations) were applied to differences among significant correlations, with appropriate adjustment of Type I error rate for multiple testing.

Separate correlations were determined for each indoor noise measure. Likewise, separate correlations were calculated for each analysis epoch and each time period following an event. Finally, dosage-response relationships were calculated for whole-night noise measures and responses.

The preferred dosage-response relationships (epoch or event and whole night) were determined on the basis of the reliability of and comparisons among the correlations. This analysis identified the preferred noise metric and epoch (or duration following an event). Similar analyses were conducted for whole night measures. Among relationships that did not differ significantly, those chosen for further analysis and discussion were the most economical and easy to implement (i.e., those of higher priority in Section 4.6.4).

4.6.5.1 Dosage-response relationships

Screening analyses were intended to identify preferred epochs or event criteria, noise metrics, response measures and transformations (if any) for predicting the effects of noise on sleep disturbance. Plots and regression equations for the selected dosage-response relationships were developed and discussed.

4.6.5.2 Multiple regression analyses

These analyses were designed to identify relationships among noise exposure levels (using the preferred metric identified in preliminary analyses), responses, and other factors affecting sleep disturbance. Different analytic strategies for event and whole night analyses were employed. Event-based analyses utilized a dichotomous scale for responses, whereas whole-night analyses utilized a continuous scale for responses.

- Multiple logistic regression analysis of events:

A direct strategy was employed to account for the effects of order of entry of predictor variables in a regression equation on the apparent importance of some variables. In a direct analysis, all variables enter the equation simultaneously, and each predictor variable (including control

Table 3 *Variables in Multiple Logistic Regression on Awakening for Individual Events.*

Type	Variables
Personal characteristics	Spontaneous awakening rate (continuous covariate) Gender (dichotomous covariate) Age (continuous covariate) Site (discrete covariate) Residence (discrete covariate to remove within-residence effects from residual variance)
Time-related characteristics	Length of time in the study (continuous covariate) Time since retiring (continuous covariate) Months in residence (continuous covariate)
Pre-sleep characteristics	Tiredness prior day (continuous covariate) Alcohol prior evening (dichotomous covariate) Medication prior evening (dichotomous covariate)
Noise characteristics	Ambient level (continuous covariate) Sound level (continuous IV)

variables) is assessed in terms of its importance to the equation after statistically adjusting for all other variables. Table 3 summarizes the predictor variables in the analysis of individual events.

- Multivariate multiple regression analysis of whole night's responses:

A direct strategy was also planned for whole night's responses, in which all predictor variables (including covariates) enter each equation simultaneously. Table 4 summarizes the predictor variables in the analysis scheme for predicting the whole night's sleep disturbance.

4.6.5.3 Supplementary analyses

A number of relationships among variables were of interest in addition to those examined in the primary analyses. These were evaluated through a series of bivariate and multiple regressions and analyses of variance. Questions to be answered through these analyses included:

- What is the relationship between the number of behaviorally confirmed awakenings each night and the number recalled the following morning?
- What is the relationship between annoyance, as reported the following morning, and the other response measures: awakening, recall of awakenings, overall sleep quality, etc.
- What is the dosage-response relationship between annoyance, as reported the following morning, and the measure of the whole night's noisiness?

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Table 4 *Variables in Multivariate Multiple Regression on Sleep Disturbance for Whole Night.*

Type	Variables
Sleep disturbance	Higher priority dependent variables (continuous covariates)
Personal characteristics	Spontaneous awakening rate (continuous covariate) Gender (dichotomous covariate) Age (continuous covariate)
Time-related characteristics	Length of time in the study (continuous covariate) Months in residence (continuous covariate)
Pre-sleep characteristics	Tiredness prior day (continuous covariate) Alcohol prior evening (dichotomous covariate) Medication prior evening (dichotomous covariate) Minutes of sleep prior night (continuous covariate)
Noise characteristics	Ambient level (continuous covariate) Sound level (continuous IV, adjusted for all covariates and sound sources)

What is the difference in noise levels of events which do and do not awaken test participants?

A detectability analysis was planned to calculate a scalar index of the sensitivity of observers to noise events. A final question was examined through analysis of variance: what is the difference in maximum A-weighted level between events that do and do not awaken residents?

5 RESULTS

This Chapter describes findings of analyses of acoustic measurements, behavioral indications of sleep disturbance, self-reports of sleep disturbance, and the relations among them. Inferential analyses are described in sections which follow those in which descriptive information is provided. Additional detail about variables and data analysis methods may be found in Appendix C.

5.1 Overview of Data Set

Table 5 presents a top level summary of the data collection effort. Complete data were available for 1887 subject-nights[4] of observations: 632 at Castle Air Force Base, 783 at LAX, and 472 from control sites. Data from one participant at Castle AFB and two at LAX were not analyzed due to inappropriate noise measurements, leaving 1823 subject-nights available for analysis. Thirty-six men and 46 women, ranging in age from 19 to 79 years (mean age = 47 years, standard deviation = 18 years), living in 45 homes, participated in the current study. Test participants' duration of residence in their homes ranged from 2 months to more than 40 years, with both a mean and standard deviation on the order of 12 years.

Table 5 *Summary of Field Data Collection.*

	Control Sites	Castle AFB	LAX
Number of Homes	12	15	18
Number of Men	10	12	16
Number of Women	13	15	19
Average Age (in years)	33.9	43.9	52.2
Number of Subject-Nights	472	632	783

Most analyses are based on relationships between noise exposure and sleep disturbance measures in this full data set. Entire-night analyses are based on a subset of 930[5] subject-nights during which test participants retired after 10:00 PM and arose before 8:00 AM, the hours during which continuous 2-second L_{eq} time histories of indoor noise exposure were available. Table 6 identifies the subsets of data used for analyses.

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[4] A "subject-night" of data represents all information collected from a test participant from time of retiring in the evening to time of awakening the next morning.

[5] One subject-night of the original 931 was eliminated due to anomalous recording of time slept.

Table 6 *Subsets of Data Used for Various Analyses.*

Database	Description	Analyses
1	1823 subject-nights with appropriate noise measurements	Screening of event-based correlations (Section 5.4.1) Screening of epoch-based correlations (Section 5.4.2) Dosage-response relationships (Section 5.5) Noise levels required to awaken (Section 5.7.4)
2	930 subject-nights during which test participants retired after 10:00 PM and arose before 8:00 AM.	Screening of entire night correlations (Section 5.4.3) Logistic regression analysis of behavioral awakening (Section 5.6) Relationship between behavioral responses and recalled awakenings (Section 5.7.1) Relationship between annoyance and sleep disturbance (Section 5.7.2) Relationship between nighttime noise exposure and annoyance (Section 5.7.3)

5.2 Description of Noise Environments at Test Sites

Table 7, Table 8, and Table 9 summarize acoustic measurements made of the noise events, epochs, and entire nights, respectively. Maximum A-levels were measured with a "fast" sound level meter response. A-weighted signal-to-noise ratios were calculated by taking the difference between the maximum A-level and the lowest level 5-minute epoch level for the particular site and night containing the noise events.

The highest mean levels and greatest variability in indoor noise event metrics were observed at Castle AFB. Mean levels of noise events observed at LAX and control sites were quite similar, even though no nighttime aircraft noise was present at the control sites. The greater variability of noise event levels at control sites than at LAX is due to smaller numbers of lower level events occurring in lower ambient levels.

Table 8 shows the average equivalent levels of 1 minute indoor noise measurement epochs for the three sites. These levels differ by less than ±2 dB across three sites. Noise levels at Castle AFB were only 4 dB higher than at the control sites.

Table 9 shows examples of all-night indoor noise metrics at the three sites. The levels were calculated from two-second time history measures taken between the hours of 10:00 PM and 8:00 AM, or the subjects' longest sleep time, whichever is smaller. The maximum L_{eq} must be smaller

Table 7 *Summary of Indoor Measurements of Individual Noise Events in Sleeping Quarters.*

SITE	STATISTIC	NOISE METRICS (dB)			
		Maximum A-Level	SEL	L_{eq}	A-weighted S/N Ratio
Control	Mean	67.3	69.4	63.0	29.4
	Standard deviation	7.7	6.6	6.3	12.3
	Range	43.2	42.9	33.6	56.9
Castle AFB	Mean	76.6	81.0	72.3	39.5
	Standard deviation	8.2	9.1	6.8	11.8
	Range	65.7	61.0	56.1	84.7
LAX	Mean	66.5	69.6	62.9	28.7
	Standard deviation	4.4	4.8	3.2	12.1
	Range	40.4	34.4	29.9	64.1

than the maximum for individual events since the L_{eq} is averaged over one minute rather than the 0.1 second associated with the "fast" meter reading. As expected, the highest noise levels of both maximum and L_{eq} for the entire night were recorded at Castle AFB. The number of events is greatest at LAX, but the total duration of the nightly events is similar at Castle and LAX. The smallest numbers and shortest durations of events were observed at the control sites.

Table 8 *Summary of Indoor Measurements of Equivalent Levels in One Minute Epochs in Sleeping Quarters.*

Site	Mean Value of 1 Minute L_{eq}
Control	37.8 dB
Castle AFB	41.5
LAX	39.5

Table 9 *Summary of Four Measures of Entire Nights' Noise Exposure in Sleeping Quarters.*

Statistic	Noise Metrics			
	Maximum L_{eq}	Nightly L_{eq}	Number of events	Total Duration of events (sec)
Control (60 dB indoor threshold)				
Mean	59.9 dB	44.5 dB	5.9	31.8
Standard deviation	6.5	5.2	18.3	126.0
Range	37.3	29.0	151	1419
Castle AFB (70 dB indoor threshold)				
Mean	68.5	51.4	11.4	125.4
Standard deviation	10.4	8.9	31.2	233.3
Range	64.4	49.4	435	2620
LAX (60 dB indoor threshold)				
Mean	60.8	45.9	20.5	126.2
Standard deviation	5.6	5.5	45.7	275.5
Range	36.8	30.4	279	1176

5.2.1 Comparison of noise events

Figure 15 compares typical cumulative distributions of indoor noise event levels at the three sites. Figure 16, Figure 17, and Figure 18 show the distributions for each site separately. Nighttime aircraft noise intrusions at Castle Air Force Base were both more numerous and of substantially higher level than at LAX. The cumulative distribution of indoor noise event levels at LAX differs little from that of control sites.
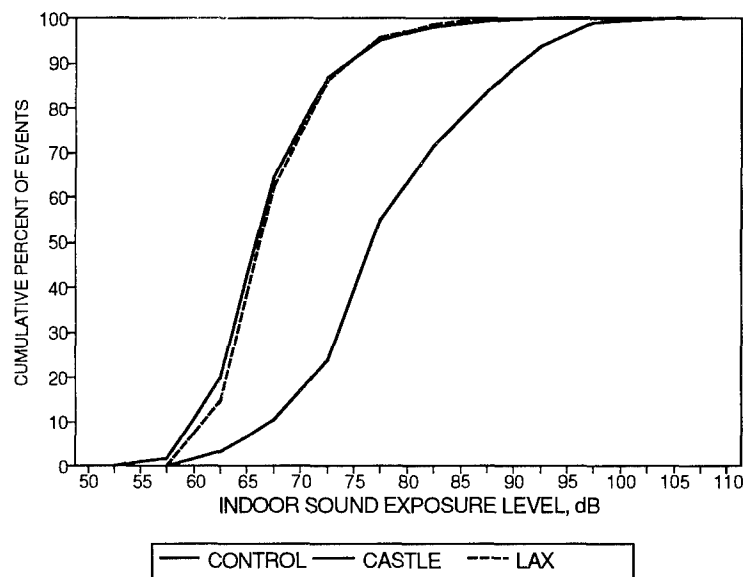
Figure 15   *Example of cumulative distributions of indoor noise event levels at three study sites.*

5.2.2   Comparison of indoor and outdoor noise levels at residences with identical outdoor noise exposure

Figure 19 illustrates the nature of differences in noise event and ambient levels that may occur in different sleeping quarters at the same site. The figure plots two-second indoor L_{eq} time histories for the same one hour time period at two adjacent homes. The homes were located approximately 3500' north of the takeoff end of the runway at Castle Air Force Base along the extended centerline. Test participants at the centrally air conditioned home (represented by the lower trace in Figure 19) reported sleeping with windows closed. Test participants at the other home (represented by the upper trace in Figure 19) reported sleeping with windows open and a fan running in the bedroom.

Given their close proximity to each other and to the end of the runway and its extended centerline, the aircraft noise exposure of the two homes was essentially identical. Nonetheless, indoor aircraft noise event levels in the sleeping quarters of the two homes differed by 13.5 dB.

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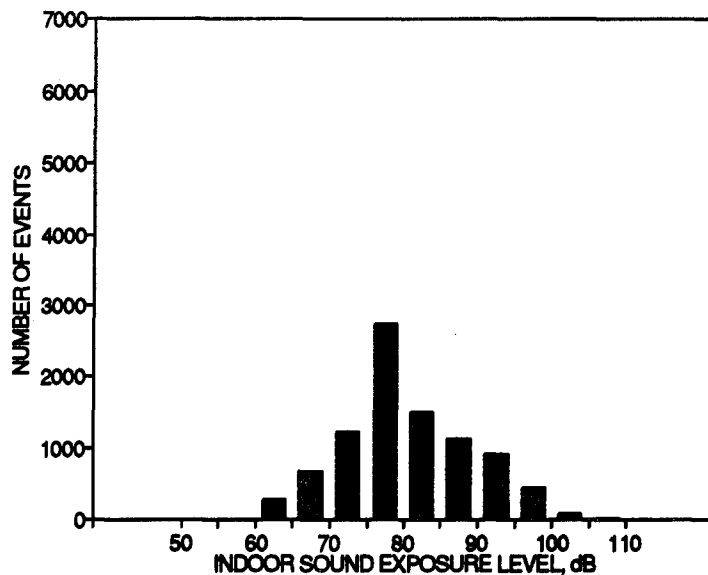
Figure 16   *Distribution of nighttime indoor noise event levels in sleeping quarters of all test participants at Castle Air Force Base.*
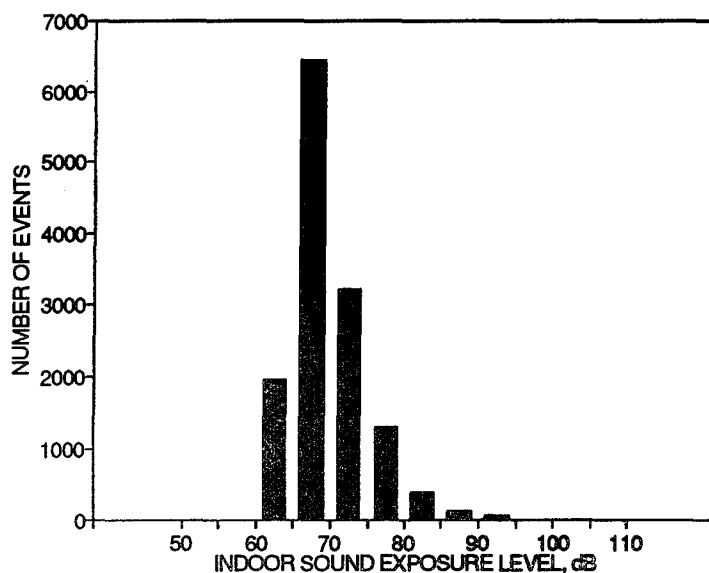
Figure 17   *Distribution of nighttime indoor noise event levels in sleeping quarters of all test participants at Los Angeles International Airport.*

Furthermore, ambient sound levels in the two sleeping quarters differed by 18 dB. Ambient levels in the sleeping quarters of one home were 6 dB higher than those recorded by an outdoor noise monitor on the property line between the two homes. Ambient levels in the sleeping quarters of the other home were 11 dB lower than those measured at the property line. Aircraft overflight levels

44
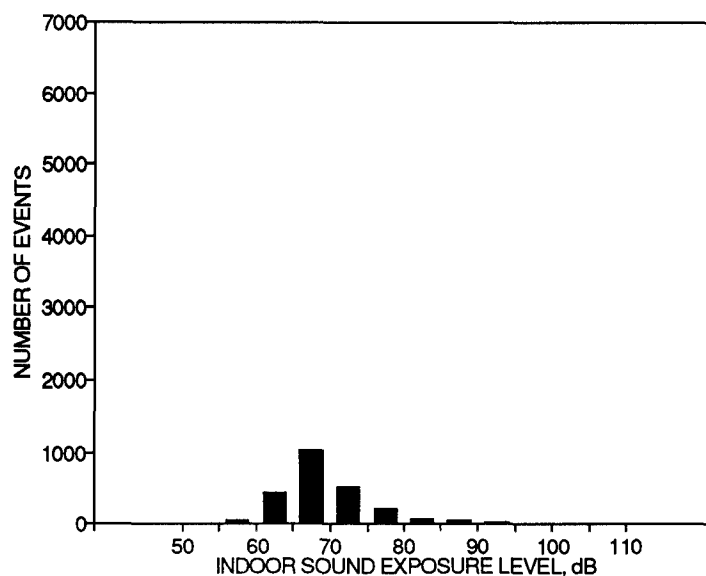
Figure 18 *Distribution of nighttime indoor noise event levels in sleeping quarters of all test participants at control sites.*

inside the home with closed windows averaged 26 dB lower than measured outdoors, while overflight levels in the home with the open windows were only 13 dB lower than measured outdoors.

5.2.3   Variability in ambient noise levels within sites

Table 10 shows ambient noise levels measured in sleeping quarters. These levels are minima of all of the 5-minute epoch averages between the hours of 10:00 PM and 8:00 AM. The average ambient levels were similar for the three sites (31 to 34 dB) but the range of ambient levels was sizeable at each site. This range in ambient levels (27-38 dB) is most likely due to noises generated inside the house.
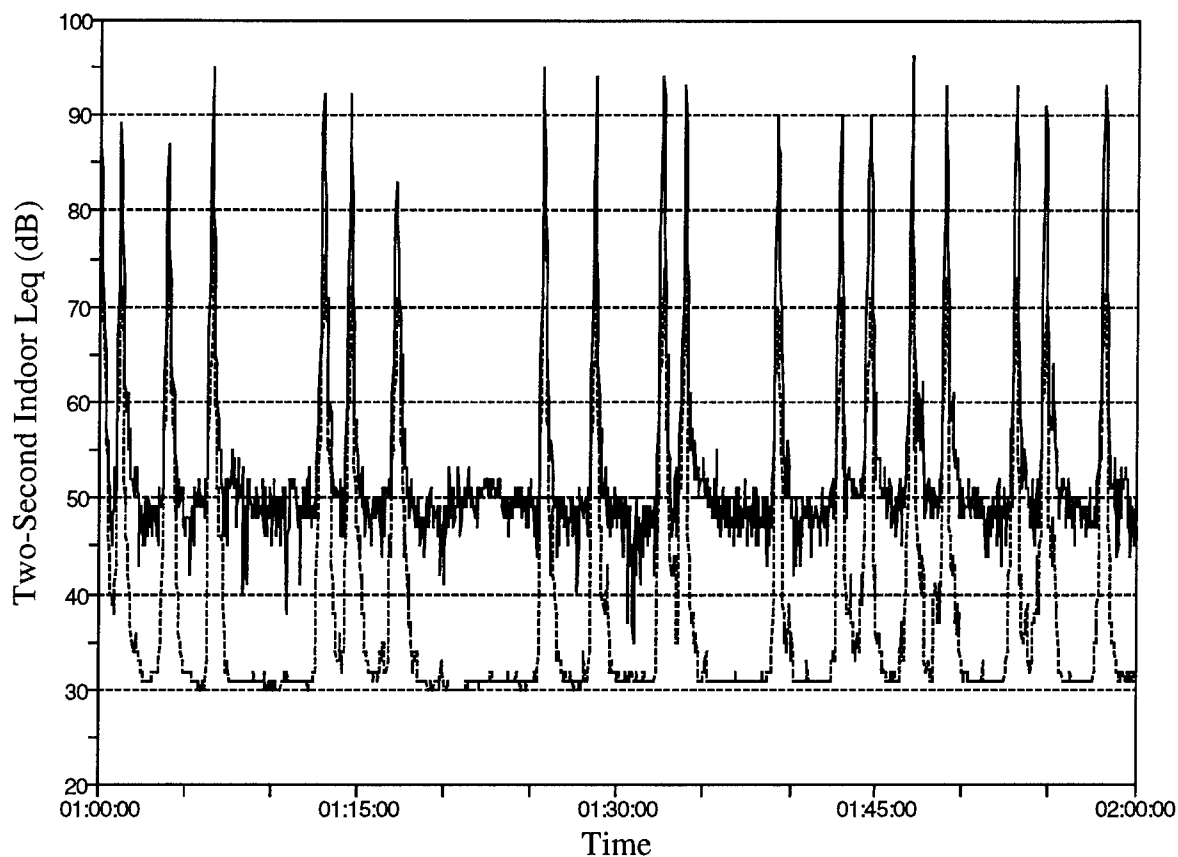
Figure 19 *Comparison of simultaneous two-second L_{eq} time histories of noise levels inside two residences near Castle Air Force Base.*

Table 10 *Average, Minimum, and Maximum Nighttime Ambient Noise Levels Derived from all Epochs With Smallest 5-Minute L_{eq} Values.*

Site	Average	Minimum	Maximum	Standard Deviation
Control	32.8 dB	23.6 dB	51.0 dB	8.3 dB
Castle AFB	33.6	23.9	52.9	7.6
LAX	30.7	22.0	59.9	6.4

5.3 Description of Response Data

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5.3.1 Behavioral responses

Table 11 contains a gross summary of the behavioral awakening data. Figure 20 shows the distribution of the numbers of noise-event related behavioral awakening responses. Figure 21 shows the distribution of numbers of non-noise related (spontaneous) behavioral awakening responses over subject-nights. Awakenings attributable to noise events (that is, occurring within five minutes after the occurrence of an event) were observed on only 16% of nights across sites. Spontaneous awakenings occurred during 85% of the nights across sites. Table 12 shows the gross numbers of events and behavioral awakening responses observed at the three study sites. (Note that not all of these responses were associated with noise events.)

The possibility that the overall response rate varied systematically with duration of study participation was assessed by plotting button pushes as a function of nights in the study. A small but reliable negative relationship was found, indicating that the number of button pushes declined slightly over the course of data collection. However, sequential study nights accounted for less than 2% of the variance in behavioral awakening responses. Therefore, data from all study nights were retained.

Table 11 *Summary of Behavioral Responses for all Subject-Nights at all Sites.*

Variable	Mean	Standard deviation	Range
Average number of spontaneous awakenings per night	2.07	1.50	0 to 9
Average number of noise-related awakenings per night	0.24	0.67	0 to 7
Average sleep duration per night	469 min	67.10	126 to 624[a]

[a] For the 930 nights on which test participants retired after 10:00 PM and arose before 8:00 AM.

5.3.2 Self-report responses

Appendix D contains information about responses to questionnaire items. Responses to nighttime questions (shown in Figure D-1 through Figure D-3) are summarized as follows: Only 13.7% of test participants reported feeling very or extremely tired during the day. Most respondents did not drink alcohol (88%) or take any medication (81%) prior to going to sleep.

Responses to the morning questions (shown in Figure D-4 through Figure D-9) are summarized as follows: Only 7% of the test participants reported sleeping not at all well, 8.5% reported feeling very or extremely tired in the morning, 80% recalled falling asleep within 20 minutes, and 75%

47
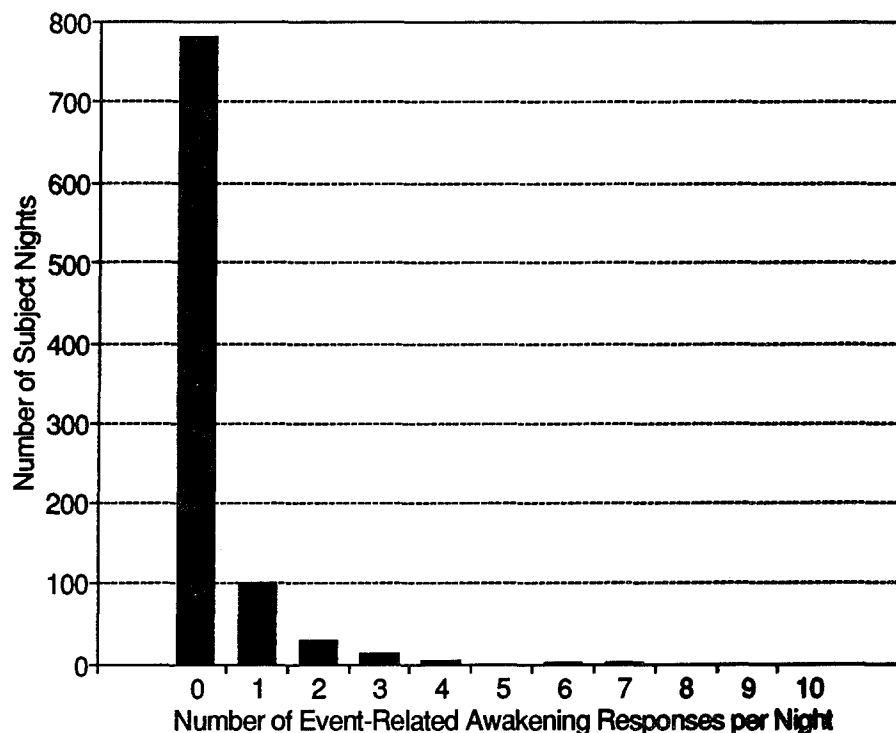
Figure 20 *Distribution of numbers of noise event-related behavioral awakening responses at all sites.*

recalled being awake for 20 minutes or less during the night. **Approximately 15% of the test participants were awakened by aircraft noise, with 15% of these respondents reporting high annoyance** to the aircraft overflights.

Table 12 *Total Numbers of Events and Behavioral Awakening Responses Observed at Study Sites.*

	Control Sites	Castle AFB	LAX
Number of Noise Events	7570	7646	18950
Number of Behavioral Awakening Responses	1043	1416	1993

The analyses described below follow the plan outlined in Figure 14 and discussed in section 4.6.
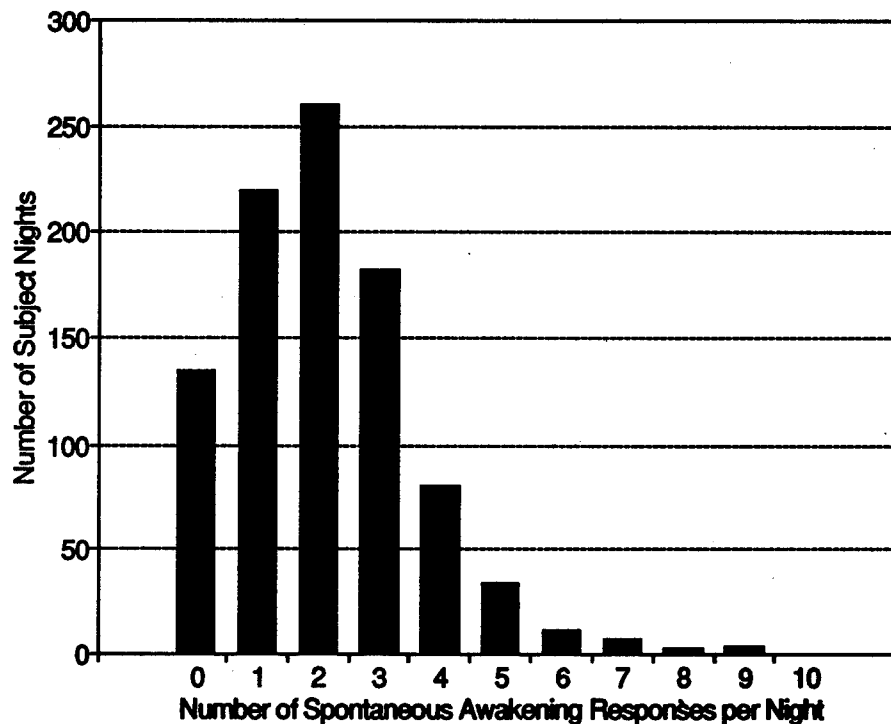
Figure 21 *Distribution of the numbers of non-noise related behavioral awakening responses over subject-nights.*

5.4 Screening of Bivariate Correlations

The first step in examining correlations among noise metrics and awakening data was to select metrics meriting further attention from among those that could be calculated from time series of A-weighted noise measurements. The large numbers of correlations compared in the screening process required adjustments to the criterion used for assessing statistical significance. In the case of the 12 single-sided tests of correlations between event-based behavioral awakenings and noise measures, a value of $\alpha = .008$ was selected. In the case of correlations between epoch-based behavioral awakenings, the 3 correlations each were tested at $\alpha = .033$. A value of $\alpha = .003$ was adopted in the case of the 36 correlations for entire night exposure and behavioral awakening responses.

5.4.1   Screening of event-based noise metrics

Table 13 shows the Pearson product-moment (linear) correlations among noise and prevalence of behavioral awakening responses within 1, 2, and 5 minutes of occurrence of noise events. No significant quadratic or higher order associations were observed in these data. The two statistically significant correlations ($r = .56$, the correlation between SEL and awakening within 5 minutes, and $r = .49$, the correlation between SEL and awakening within 2 minutes) were not reliably different from one another. Behavioral awakening within 5 minutes was selected as the more inclusive

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indication of awakening, and SEL as the preferred metric of noise exposure (highest priority in Section 4.6.4.1), for further analyses of the ability of noise events to disturb sleep, based on their higher corrlation values.

Table 13 *Correlations between Probability of Awakening and Individual Noise Event Levels.*

Post-Event Interval	Maximum A-Level	SEL	L_{eq}	A-weighted S/N
Within 1 minute	.32	.45	.23	.38
Within 2 minutes	.35	.49*	.27	.36
Within 5 minutes	.42	.56*	.34	.38

* $p < .008.$

5.4.2 Screening of epoch-based noise metrics

Correlations between behavioral awakening responses and L_{eq} values of 1, 2, and 5 minute epochs prior to button pushes appear in Table 14. Only the correlation between behavioral awakening and the L_{eq} in the preceding 1 minute epoch ($r = .43$) was statistically significant.

Table 14 *Correlations between Probability of Awakening and Noise Levels in Analysis Epochs.*

Epoch duration	L_{eq}
1 minute	.43*
2 minute	.29
5 minute	-.13

* $p < .033.$

5.4.3 Screening of entire night noise metrics

Table 15 displays correlations among four noise exposure variables with eight self-report and one behavioral variable for entire nights. Seven correlations were statistically significant ($\alpha = .003$) in this set, of which three were related to sleep disturbance. Report of awakenings by aircraft noise was weakly related to the two L_{eq} measures and the number of noise events was weakly related to sleep latency. Since the largest of these correlations accounted for no more than 2.5% of the variance in the data, however, no further analyses of self-reported or behavioral sleep disturbance on the basis

of entire noise metrics were undertaken. Similarly, the relationships between noise measures and annoyance ratings accounted for little variance.

Table 15 *Correlations between Independent (columns) and Dependent (rows) Variables based on Entire Night Noise Metrics.*

	Maximum L_{eq}	Night L_{eq}	Number of events	Duration of events
Sleep latency (in minutes)	.07	.08	.10*	.10
Number of recalled awakenings	-.04	-.08	-.06	-.04
Awakened by aircraft noise	-.16*	-.16*	-.01	-.08
Sleep quality rating	-.04	-.05	.10	.07
Total sleep time	.14	.28	.18	.19
Annoyance rating	.15*	.17*	.15*	.18*
Tiredness rating	.06	.01	-.16	-.14
Reported time awake	.00	.04	.03	.03
Behavioral awakening responses	-.08	-.10	-.11	-.08

*$p < .003$

5.5 Dosage-Response Relationships for Two Measures of Noise Exposure

Figure 22 illustrates a dosage-response relationship derived from a linear regression of indoor SEL of noise events on the prevalence of behavioral awakenings (i.e., button pushes) occurring within five minutes of the event. Figure 23[6] replots the same data with an exaggerated vertical scale to display data points and errors of estimate more prominently. Figure 24 and Figure 25[7] are parallel figures which show the dosage-response relationship derived from a linear regression of indoor L_{eq} on the prevalence of awakening within one minute epochs.

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[6] The calculation for N is based on 12 noise intervals at 3 sites. The total N is 30 rather than 36 because noise events were not present in each interval at all sites.

[7] The calculation for N is based on 14 intervals at 3 sites. The total N is 40 rather than 42 because noise events were not present in each interval at all sites.
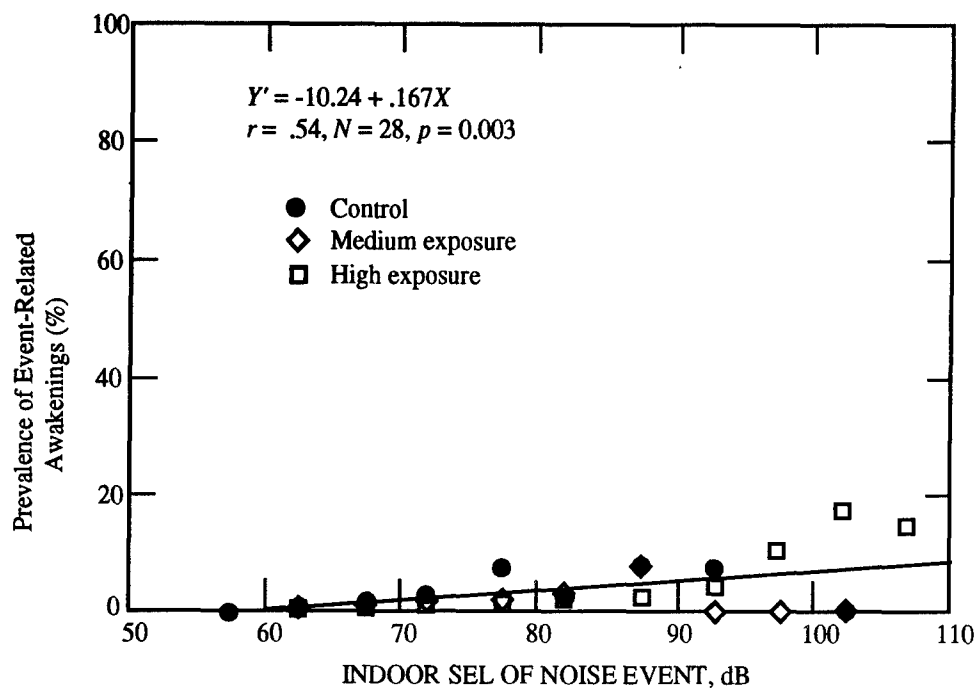
Figure 22   *Prevalence of behavioral awakening responses occurring within five minutes of noise events, aggregated by test participants within sites, in 5 dB increments.*

The strengths of the relationships between the two predictor variables (SEL of events and L_{eq} of epochs) and the prevalence of awakenings (button pushes) do not differ significantly from one another ($p > .05$).

5.6   Logistic Regression Analysis of Predictability of Behavioral Awakening Responses

Logistic regression is preferred when the predicted variable represents the probability of group membership (in this case, awakening confirmed by a button push) and predictor variables are a mixture of discrete and continuous measures.   Unlike discriminant function analysis, logistic regression makes no assumptions about distributions of continuous measures.   Unlike other multivariate analyses in which the independent contributions of each predictor variable are expressed in terms of variance accounted for, the contributions of predictor variables in multivariate logistic regressions are expressed in terms of odds ratios.

A direct logistic regression analysis was performed on the occurrence of a behavioral awakening response in the presence of a noise event as the outcome variable and several predictor variables: indoor sound exposure levels of noise events, gender, age, duration of residence, sequential study night, L_{eq} of ambient noise in sleeping quarters, presumed event source (aircraft-related or other), time since retiring, self-reported alcohol and drug consumption, tiredness before retiring, and spontaneous

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$Y' = -10.24 + .167X$
$r = .54, N = 28, p = 0.003$

● Control
◇ Medium exposure
□ High exposure

15

10

5

0

Prevalence of Event-Related Awakenings (%)

50   60   70   80   90   100   110

INDOOR SEL OF NOISE EVENT, dB
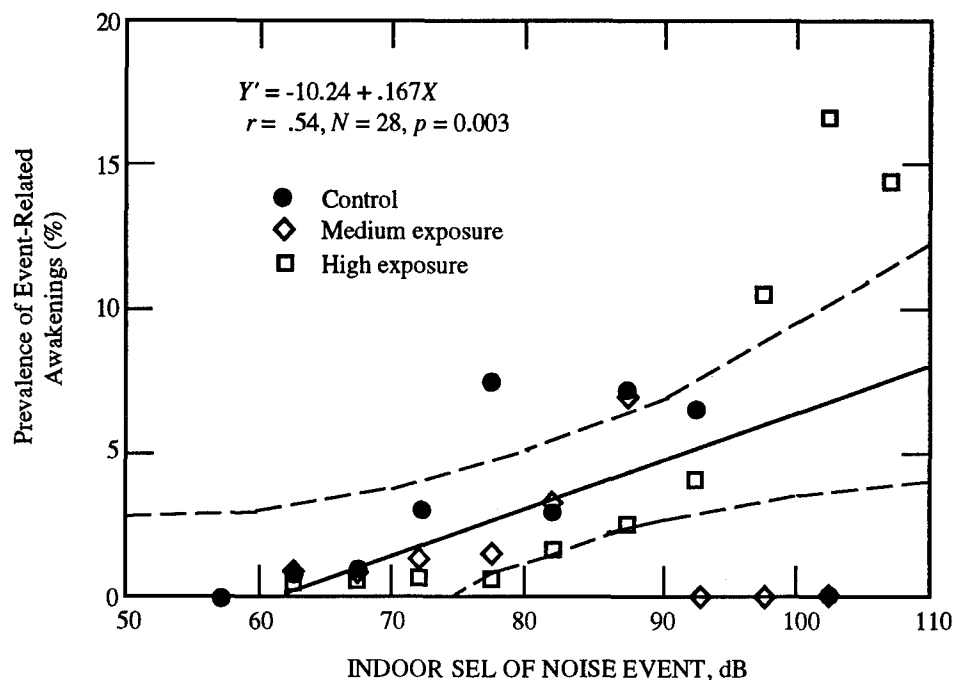
Figure 23   *Prevalence of behavioral awakening responses occurring within five minutes of noise events, aggregated by test participants within sites, in 5 dB increments. (Note exaggeration of vertical scale.)*

(non-event related) awakenings. Responses of 81[8] test participants to a total of 10096 events were analyzed. These included 326 noise events followed by awakening responses within five minutes and 9770 noise events which failed to awaken test participants within five minutes.

The predictive model of behavioral awakening derived from the logistic analysis was tested in two ways. First, the model containing all predictors was tested against a chance model: one which contains only the intercept. The statistically significant result, $\chi^2(12, N = 10096) = 376.07, p < .001$, indicates that prediction of behavioral awakening by the full prediction model is better than would be expected by chance. A stronger test of the model evaluated how closely the behavioral awakening responses predicted by the model matched the observed awakenings. The lack of a significant discrepancy between the predicted and observed behavioral awakenings (Hosmer-Lemeshow $\chi^2(8, N = 10096) = 11.70, p = .165$), indicates a model that adequately fits the data.[9]

Table 16 shows regression coefficients, odds ratios, 95% confidence intervals for odds ratios, and the contribution of each of the predictors to the model. Regression coefficients (B) are of limited value in this nonlinear analysis, but are useful as indications of the direction of relationship of each

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[8] One case with anomalous responses was omitted.

[9] A goodness-of-fit statistic indicates an adequate model fit unless the p value is very small (e.g., less than .05).
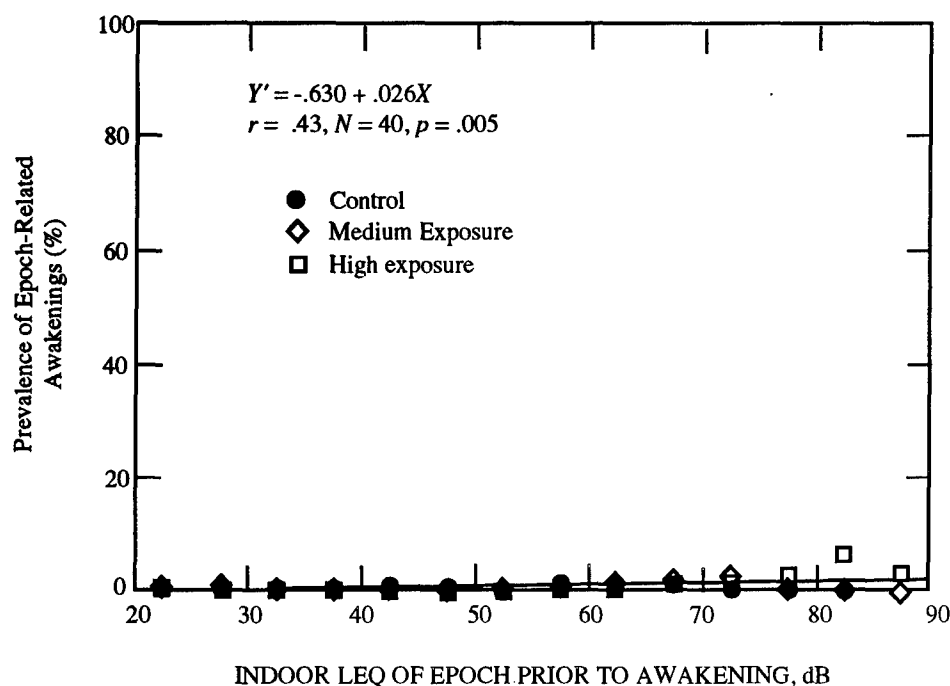
Figure 24   *Prevalence of behavioral awakening responses as a function of L_{eq} of prior one minute epoch, aggregated by test participants within sites, in 5 dB increments.*

predictor with the probability of awakening. Positive coefficients indicate that an increase in the value of the predictor results in an increase in the probability of awakening. The relative magnitudes of the coefficients do not indicate the relative strength of unique contribution to prediction of each variable, because variables are measured on different scales.

The odds ratio is a more easily interpreted transformation of the regression coefficient, defined as e^B. An odds ratio that is greater than one indicates not only that the likelihood of awakening increases with increasing magnitude of the predictor, but also the extent of increase in likelihood. For example, an odds ratio of 2 indicates that as the predictor increases by one unit, the odds in favor of awakening doubles. Regression coefficients and their associated odds ratios are estimated values, subject to sampling error. The 95% confidence limits bound the likely range of values (odds ratios) given the sample data. A variable significantly enhances prediction of awakening if the confidence limits on its associated odds ratio do not include 1.0.

The final column of Table 16 presents the results of a series of analyses in which models are formed with each predictor separately removed from the full model containing all predictors. The performance of the reduced model for each predictor is then compared with the full model. A statistically significant result indicates that the model without a given predictor does a significantly poorer job of predicting awakening than one which includes that predictor, and thus serves as a test of the significance of prediction for that variable. This latter test is preferable to tests of variables based on confidence limits for odds ratios.

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$$Y' = -.630 + .026X$$
$$r = .43, N = 40, p = 0.005$$

- ● Control
- ◇ Medium Exposure
- □ High Exposure

Prevalence of Epoch-Related Awakenings (%)

INDOOR LEQ OF EPOCH PRIOR TO AWAKENING, dB
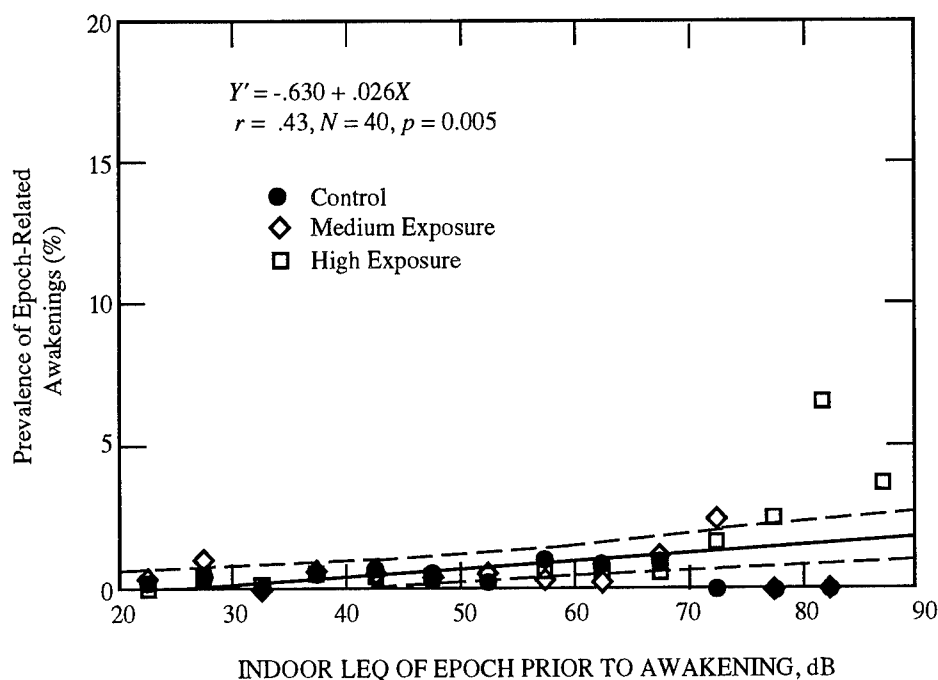
Figure 25   *Prevalence of behavioral awakening responses as a function of L_{eq} of prior one minute epoch, aggregated by test participants within sites, in 5 dB increments. (Note exaggeration of vertical scale.)*

Seven variables successfully predicted behavioral awakenings associated with noise events in an analysis in which all predictors were statistically adjusted for all other predictors. Sound exposure levels of events were positively related to behavioral responses such that each 1 dB increase in SEL increased the odds of awakening by a factor of 1.06. Time since retiring was also positively related to awakening; the longer the participant had slept, the greater the likelihood of awakening to a noise event. For each 15 minutes since retiring, the odds of awakening to a noise event increased by 1.06.

Time since retiring was the single strongest predictor of awakening in the presence of a noise event. Figure 26 plots behavioral awakening as a function of time since retiring. The probability of awakening (on the left ordinate) is depicted in the bars, whereas cumulative probability of awakening (on the right ordinate) is depicted by the curve.

Duration of residence (in months) was positively but trivially related to awakening (the increase in odds ratio was less than .01)[10]. Rating of tiredness in the evening interview had a strong relationship with awakening to noise events, with an increase in odds of 1.26 for each one category

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[10] The total range of duration of residence was 2 months to more than 40 years. The few participants who had been living at their current residences fewer than 6 months contributed only about 10% of the subject-nights analyzed.

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Table 16 *Regression Coefficients, Odds Ratios with Confidence Intervals, and Significance of Removing Predictor Variables from a Logistic Regression Model of Event-Based Awakenings.*

Variable (unit)	B	Odds Ratio per unit	95% Confidence Interval for Odds Ratio		F to Remove df=1, 10083
			Lower	Upper	
Personal Characteristics					
Number of spontaneous awakenings	-0.295	0.74	0.67	0.82	42.41*
Gender (category)	-0.048	0.95	0.75	1.21	0.19
Age (years)	-0.021	0.98	0.97	0.99	18.46*
Time-Related Characteristics					
Time since retiring (in 15 minute increments)	0.059	1.06	1.05	1.07	167.39*
Duration of residence (months)	0.002	1.00	1.00	1.00	22.67*
Number of nights in study	0.008	1.01	0.99	1.02	1.47
Pre-Sleep Characteristics					
Alcohol (category)	0.047	1.05	0.69	1.60	0.06
Medications (category)	-0.082	0.92	0.66	1.30	0.28
Tiredness on retiring (scale of 1 to 5)	0.233	1.26	1.13	1.43	16.72*
Noise Characteristics					
Ambient level (dB)	-0.055	0.95	0.93	0.96	57.35*
Presumed noise source (category)	0.171	1.19	0.87	1.61	1.52
SEL (dB)	0.058	1.06	1.04	1.08	73.43*

* $p < .001.$

increase in self-rating (ranging from 1 = not at all tired to 5 = extremely tired.)

Ambient noise levels in sleeping quarters were negatively related to behavioral awakening. Each 1 dB increase in ambient noise level reduced the odds of awakening in the presence of a noise event

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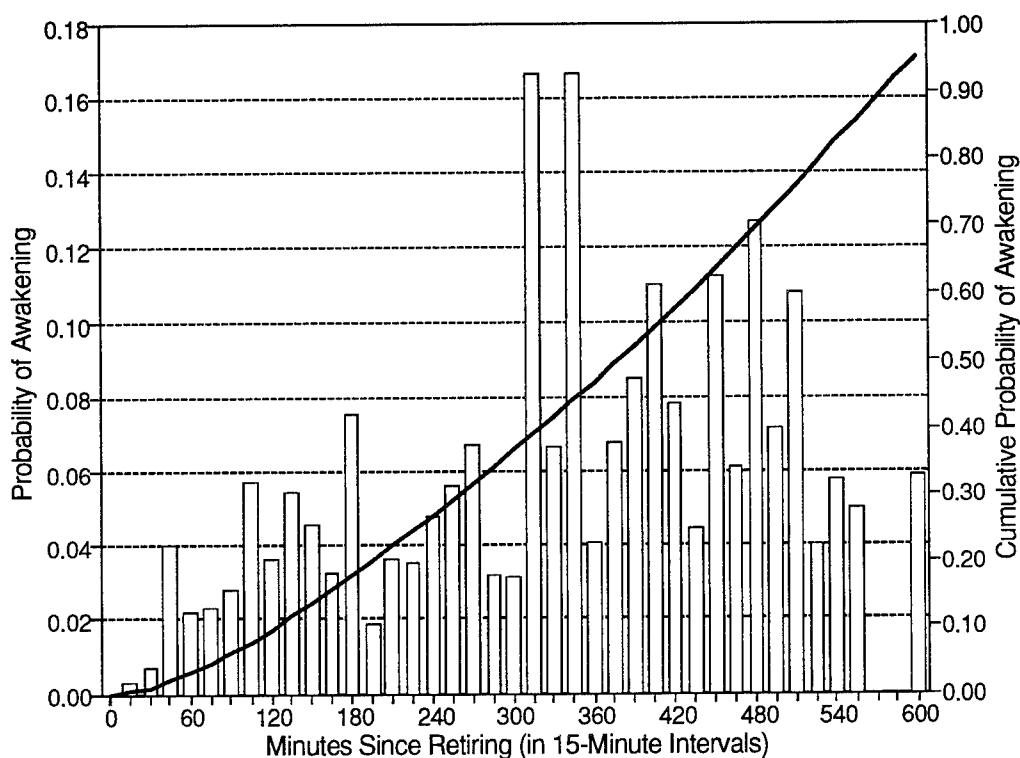
Figure 26 *Relationship between time since retiring and behavioral awakening in the presence of a noise event.*

by a factor of .05. The number of spontaneous awakenings for the night was also negatively related to awakening due to noise events. An increase of one spontaneous awakening lowered the odds of awakening to a noise event by a factor of .26. Age showed a small negative relationship with awakening in the presence of a noise event, with a factor of .02 decrease in odds of awakening with each year of age.

Prediction based on SEL alone was unimpressive, though statistically significant. A logistic predictive model based on SEL alone accounted for only 5% of the variance in awakening[11]. A model based on SEL alone correctly predicted 97% of nonawakenings. That is, for 97% the events that did not awaken participants, the model's predicted probability of awakening was less than .50; for 3% of the events that did not awaken participants, the predicted probability of awakening was .50 or greater. However, only 5% of the awakenings were correctly predicted. That is, for 95% of the

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[11] Logistic regression analysis tends to underestimate variance accounted for in this application. For example, bivariate regression on probability of awakening as a function of SEL yields an estimated 30% of variance in awakening accounted for by SEL. This is likely to be due to the greater variability inherent in dealing with individual events rather than aggregations of events over nights in the study.

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awakenings that did awaken respondents, the model's predicted probability of awakening was less than .50; for only 5% of them was the predicted probability .50 or greater.

Adding the set of covariate predictor variables to SEL significantly improved predictability, $\chi^2(11, N = 10096)$, $p < .001$. The model with all predictors included accounted for 13% of the variance in awakening. The correct predictions of non-awakening remained at 97%. However, the correct predictions of awakening rose from 5% to 8% with the addition of other predictors to SEL.

5.7 Supplementary Planned Analyses

5.7.1 Relationship between behavioral responses and recalled awakenings

There was no significant difference between the number of awakenings recorded by button pushes and the number recalled the following morning. The two indicators of awakening were related, $r(928) = .69, p < .001$, for the 930 subject-nights on which test participants retired after 10:00 PM and arose before 8:00 AM.

5.7.2 Relationship between annoyance and sleep disturbance

A hierarchical multiple regression analysis evaluated prediction of annoyance due to aircraft noise from measures of sleep disturbance over the whole night. The first set of variables entered consisted of behavioral measures: number of button pushes signalling awakenings and time slept. Recall of number of awakenings and of sleep latency were subsequently entered to determine whether they improved the predictability of annoyance ratings. Morning attitude measures (sleep quality and tiredness) were entered last. As a whole, 12% of the variance in annoyance was predicted by the set of variables.

All three sets of variables significantly predicted annoyance, as seen in Table 17. Individually, four of the six variables contributed significantly to prediction of annoyance due to aircraft noise. Time slept, number of recalled awakenings, and time to fall asleep were positively related to annoyance; sleep quality was negatively associated with annoyance.

5.7.3 Relationship between cumulative nighttime noise exposure and annoyance

No statistically significant relationship was found between noise exposure of the entire night, as measured by L_{eq} in the time elapsed between retiring and the final behavioral awakening response, and the probability of consequential annoyance (self-reports of high or extreme annoyance).

Table 17 *Hierarchical Regression of Several Study Variables on Annoyance Rating.*

Variables	Regression Coefficient	Standardized Regression Coefficient	sr^2 (inc)
Behavioral			.069**
Awakening	0.03	0.05	
Time slept	0.002	0.12**	
Recall			.045**
Recalled awakenings	0.14	0.19**	
Latency	0.11	0.09**	
Attitudinal			.016**
Sleep quality	-0.13	-0.12**	
Morning tiredness	0.05	0.04	
Intercept	= -0.56		
$R^2 = .36$			
Adjusted $R^2 = .13$			
$R = .12^{**}$			

$^{**} p < .01.$

5.7.4 Noise levels required to awaken

Two groups of events were formed on the basis of association with awakening. An analysis of variance on the SEL of indoor noise events revealed a small but statistically significant difference, $F(1, 10094) = 167.78$, $p < .001$, $\eta^2 = .02$. On average, events that awakened test participants were higher in level (mean = 80.6 dB) than were events that failed to awaken them (mean = 74.1 dB).

5.8 Post Hoc Analyses

5.8.1 Differences in responses among sites

Multiple discriminant function analysis was used to investigate differences among the three sites in responses for an entire night. Differences were examined among behavioral awakenings, sleep time, recalled awakenings, time since retiring, ratings of sleep quality, annoyance, tiredness the previous night, time awake, number of noise-induced awakenings, and spontaneous awakening rate. The differences among sites on the 10 response measures combined were statistically reliable,

multivariate $F(20, 1836) = 8.09$, $p < .001$. Sixteen percent of the variance in the set of responses was associated with site. No significant differences among sites were observed in behavioral awakening, sleep time, time since retiring, or numbers of noise-induced and spontaneous awakenings.

However, five of the self-reports variables were significantly different across sites, after statistically adjusting for all other variables and setting $\alpha = .001$ for multiple testing and post hoc analysis. Recalled number of awakenings was greatest for LAX (mean = 2.59 per night), followed by Castle AFB (mean = 2.11) and controls (mean = 2.04). Self report of sleep quality was also greatest for LAX (mean = 3.2 on a scale of 1 to 5), followed by Castle AFB (mean = 2.94) and controls (2.86). Self reports of time awake during the night were greatest for Castle AFB (mean = 2.02 on a scale of 1 to 5), followed by LAX (mean = 1.96) and controls (mean = 1.68). Tiredness the previous evening was also greatest for Castle AFB (mean = 2.53 on a scale of 1 to 5), followed by controls (mean = 2.38) and LAX (mean = 2.24). Finally, annoyance due to aircraft noise was greater at LAX (mean = 1.49 on a scale of 0 to 5) and Castle AFB (mean 1.41) than for controls (mean = 1.01).

5.8.2   Differences between weekend and mid-week nights at Castle AFB

Nighttime training operations at Castle AFB occurred on weekdays only. Differences between weekday and weekend noise levels and responses were evaluated for 90 weekend nights and 258 mid-week nights. Analysis of variance of indoor nighttime L_{eq} showed a significant difference between weekday and weekend nights, $F(1, 345) = 25.65$, $p < .001$. Average L_{eq} for mid-week nights was 53.5 dB, while for weekend nights the average dropped to 47.7 dB. However, only 7% of the variance in sound level was associated with time of week.

Logistic regression analysis was used to evaluate differences in behavioral awakening responses, time slept, recall of time to fall asleep, and ratings of tiredness, sleep quality, and annoyance between mid-week nights and weekend nights. The predictive model produced by the set of responses was significantly better than a chance model, $\chi^2(6, N = 348) = 17.76$, $p < .01$ on discriminating mid-week from weekend nights. Evaluating each predictor at $\alpha = .008$ to compensate for multiple testing, one variable predicted time of week, after adjusting for all other predictors. Annoyance due to aircraft noise was significantly diminished during the weekend, Wald $z = -2.62$. The odds ratio for annoyance was .80, with 95% confidence limits between .67 and .95. Behavioral awakening responses did not differ reliably by day of week.

6 DISCUSSION

This Chapter discusses findings reported in Chapter 5 and inferences drawn from them.

6.1 Contribution of Outdoor Noise Events to Indoor Noise Environment

The shapes of the cumulative distributions of indoor noise event levels shown in Figure 15 resemble those described by Fidell, Horonjeff and Green (1981). As noted by Fidell *et al.* (1991), plots of cumulative distribution functions in populated areas can often be decomposed into two fairly linear segments of different slope. The lower centiles of the distribution are usually represented by a line with a steep slope (low variance), while the upper centiles of the distribution are usually represented by a line with a shallower slope (higher variance). This situation arises when the overall noise environment is the sum of distinct local and distant processes. In the case of noise events in sleeping quarters, it seems likely that a local (indoor) process with a low mean and variance is responsible for most of the events up to about the 10th centile (L_{90}), while a distant (outdoor) process with a high mean and variance is responsible for the remainder of the distribution of noise event levels in sleeping quarters. In other words, the noise environments of sleeping quarters in this study were probably composed of events of indoor origin as much as about 90% of the time. Events of outdoor origin affected the indoor noise environment only about 10% of the time.

6.2 Importance of Differences in Noise Exposure Among Sites

Tables 3 through 5 and Figures 2 and 14 document a variety of differences between long and short term measures of indoor and outdoor levels of cumulative noise exposure and of individual events at the test sites. These include sizable differences in long term average values of outdoor noise environments, as well as sizable differences in single event levels and ambient levels in sleeping quarters. Some of these differences are more directly relevant to prediction of noise-induced sleep disturbance than others.

For example, differences among sites in values of long term (24 hour), cumulative measures of outdoor noise environments, although large in some cases, proved to have little to do with behavioral awakening. To the extent that DNL values at sites are controlled by disproportionate numbers of high level noise events (such as aircraft overflights or street traffic) during daytime hours, and to the extent that indoor noise sources control ambient levels in sleeping quarters, cumulative measures of outdoor noise levels are of only secondary interest for present purposes. Although useful for predicting the prevalence of annoyance in residential settings, such measures do not adequately characterize the aspects of noise intrusions that are useful for predicting sleep disturbance.

6.3 Relationships between Noise Exposure Metrics and Behavioral Awakening Responses

The only reliable measure of the level of a noise event that predicted awakening within two and within five minutes after a noise event was SEL. These relationships, although reliable, were small. The larger accounted for about 30% of the variance in awakening within 5 minutes. A 10 dB increase in SEL was associated with an increase of only 1.6% in prevalence of awakening.

Only one of the three measures of noise levels within epochs reliably predicted behavioral awakening: L_{eq} in a 1-minute epoch reliably predicted awakening, but accounted for less than 20% of the variance in behavioral awakening responses. A 10 dB increase in the L_{eq} value of an epoch preceding an awakening predicted an increase of 0.25% in prevalence of awakening.

The dosage-response relationships illustrated in Figure 23 and in Figure 25 show considerable heteroscedasticity: the range of responses grows as the noise exposure of events and epochs increases. Many respondents failed to awaken even at the highest exposure levels. Failure to awaken at high noise levels was especially prominent at control sites and LAX.

Only two of the 36 combinations of noise measures and responses based on an entire night showed statistically reliable associations between higher noise exposure and sleep disturbance or other negative outcomes. L_{eq} for the entire night was reliably associated with self report of annoyance the following morning, but accounted for less than 4% of the variance in annoyance. Number of noise events during the night accounted for 1% of the variance in self-report of time required to fall asleep.

6.4 Discussion of dosage-response relationships

Dosage-response relationships were subject to heteroscedasticity; probability of awakening became more variable with increasing noise. This is at least partially an artifact of the rarity of extremely high noise levels. Thus, in the figures it appears that the site with the highest noise levels, Castle AFB, is the only one in which prevalence of awakening increases with noise at the upper levels. However, the failure of high noise levels to awaken residents at LAX and control sites is largely a function of their minuscule number.

This heteroscedasticity has little effect on the regression, however, which is primarily controlled by the lower noise levels. Thus, ignoring sound levels in excess of 90 dB SEL or 70 dB L_{eq} would not degrade the dosage-response relationship.

6.5 Discussion of Logistic Multiple Regression

The goal of the logistic multiple regression analysis was to quantify the unique ability of various measures to predict behavioral awakening in the presence of a noise event.

A model that included indoor SEL in addition to other personal, time-related, questionnaire, and noise measures predicted 13% of the variance in behavioral awakening in the presence of a noise event. A model based on SEL alone predicted only 5% of the variance in awakening. Thus, SEL alone accounted for less than half of the predictable variance.

Variables demonstrating statistically significant positive relationships with behavioral awakening, in addition to SEL, were time-related: time since retiring, duration of residence, and number of nights in the study. Variables demonstrating statistically significant negative relationships with behavioral awakening were spontaneous awakening rate, age, tiredness the previous night, and ambient level. The strongest single predictor of awakening was time since retiring, followed by indoor SEL. Odds of awakening increased by a factor of 1.06 for each increase of 15 minutes since retiring, and also for each decibel increase in indoor SEL.

Because so few events awakened participants, the logistic model predicted non-awakenings far more accurately than awakenings. Whether the model was based on SEL alone or SEL in addition to other predictors, 97% of non-awakenings were correctly predicted (based on a .50 cutoff for prediction). Correct predictions were made for 5% of the events that awakened participants on the basis of SEL alone, and for 8% of the events when the model included other variables.

6.6 Discussion of Accuracy of Prediction of Logistic Regression

The performance of the logistic regression model in predicting awakening may be summarized by a receiver operating characteristic (ROC) curve. An ROC curve plots the probability of a correct decision - a "hit" - against the probability of an incorrect decision - "false alarm" - to show the entire range of performance (ratios of hits to false alarms) that a decision maker (a statistical prediction model in this case) can exhibit. Figure 27 shows two such ROC curves: one for predicting awakening based on the SEL of a noise event alone, and one for the logistic regression model including all predictor variables. The ROC curve for the performance of SEL alone as a predictor variable had a $d' = 0.64$, whereas the ROC curve for the performance of a model based on all of the predictor variables had a $d' = 0.79$.

6.7 Implications of Findings about Mechanisms of Noise-Induced Awakening

This section presents several perspectives on the implications of the present findings. These interpretations are based on the overall pattern of findings, including observations that long term cumulative noise exposure measurements provided no useful basis for predicting awakenings, that sound exposure levels of discrete noise events accounted for about a third of the variance in the behavioral awakening responses, and that noise levels in epochs preceding awakenings accounted for less variance.
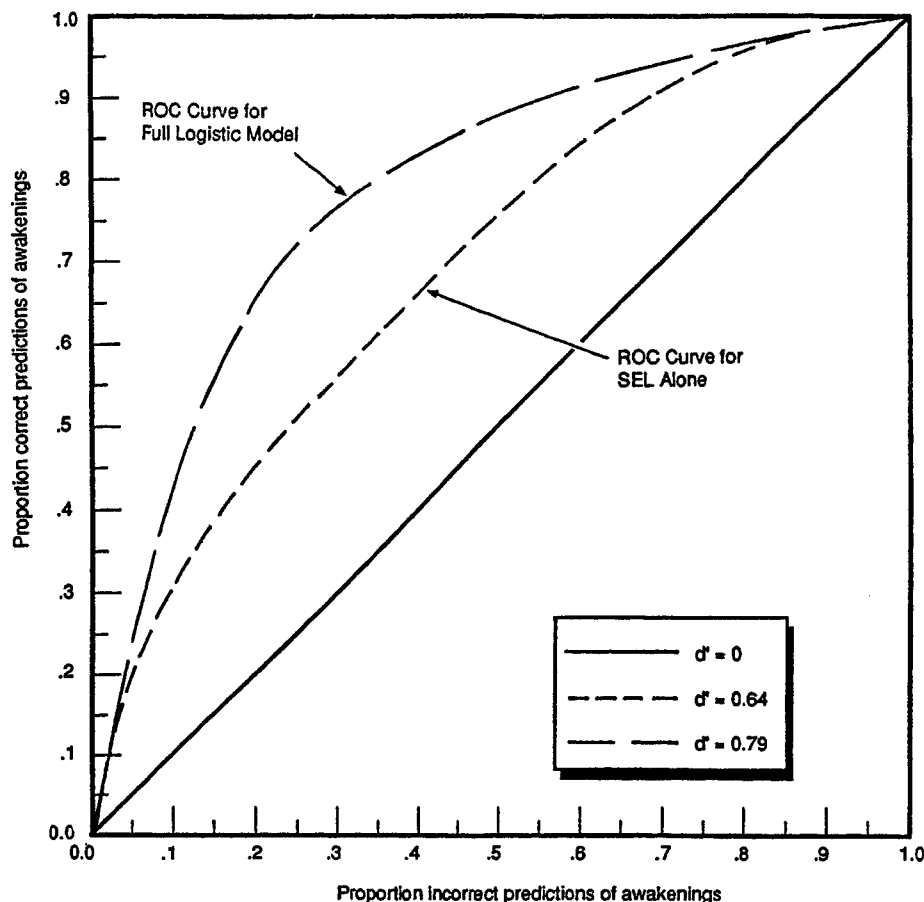
Figure 27 *Receiver Operating Characteristics (ROC) for logistic regression model based on SEL as a sole predictor and on a model with all predictor variables.*

6.7.1 Implications for equal energy hypothesis

The present findings permit several inferences to be drawn about the alternative models of awakening discussed in Section 3. Most fundamentally, it is clear for the range of noise exposure values studied that the long term acoustic energy of the sleeping environment has little if any association with sleep disturbance. The failure to account for any appreciable variance in awakening data of the analyses based on "entire night" noise measurements (that is, total noise energy from retiring to awakening) indicates that strict application of the equal energy hypothesis is unhelpful for purposes of predicting sleep disturbance.

The ability of sounds to awaken people is sensitive to the manner in which noise energy is packaged: small amounts of noise energy distributed over long periods of time are far less likely to awaken people than large amounts of noise energy concentrated within short periods of time (i.e., discrete noise events). The present findings do not support meaningful characterization of sleep interference in terms of DNL values of community noise environments.

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6.7.2   View of awakening as an event-detection process

The relationships observed in the present study between noise metrics and behavioral awakening responses suggest that noise-induced awakening may be productively modeled as an event-detection process. Sleep is apparently disturbed by short term changes in noise exposure rather than by steady state conditions. Put another way, an awakening can be treated as the outcome of a decision that a change of sufficient magnitude has occurred in the short term noise environment. The decision maker may be viewed as an homunculus (such as a pre-cognitive neural process in the peripheral auditory system that is closely coupled to attentional mechanisms) that never sleeps.

Any decision making process may be characterized by the ratio of "hits" (assertions that a signal is present when it truly is present) to "false alarms" (assertions that a signal is present when it is in fact absent) that can be achieved (Green and Swets, 1966). The standard index of sensitivity is a scalar quantity known as d'. When $d' = 0$, a detector has no information about the presence or absence of a signal and is thus is completely insensitive to it. When $d' = 4$, a detector can make essentially perfect decisions about the presence or absence of a signal.

A subset of the present data contains information from which it is possible to make a gross estimate of the sensitivity of sleepers as detectors of noise intrusions. Analysis epochs may be viewed as "trials" (opportunities to make detection decisions); behavioral awakening responses within one minute of the time of occurrence of noise events may be viewed as hits; and behavioral awakening responses occurring at any other times may be defined as false alarms. Complete information about numbers of trials is available for 930 subject-nights at all sites during which participants retired after 10:00 PM and arose before 8:00 AM.

The gross hit rate (as defined above) for all test participants in this subset of data was 4%, while the gross false alarm rate was 2.4%. Under conventional assumptions about the shapes and variances of distributions of epochs with and without noise event signals, the value of the sensitivity index, d', which corresponds to this ratio of hits to false alarms is 0.23. This value of d' reflects a sensitivity to sounds that is at least an order of magnitude lower than one typical of people in an alert state.

6.7.3   Lack of strong dependence between awakening and noise levels of events of external origin

Ollerhead *et al.* (1992) found that the relationship between outdoor noise levels and sleep disturbance did not depend on whether windows were opened or closed in sleeping quarters. It is difficult to interpret this finding if it is assumed that sleep disturbance is a strong and exclusive function of the sound level of noise intrusions in sleeping quarters. The range and locus of noise exposure measurements in the present study, as well as the dosage-response relationship between indoor SEL values and behavioral awakening observed, both aid interpretation of this seeming inconsistency.

Two explanations for Ollerhead's observation are consistent with information revealed by indoor noise measurements in the present study:

- The slope of the relationship between indoor sound exposure levels of noise events and prevalence of awakening is so shallow that a study of reasonable size would not be likely to reveal a significant difference in awakening rates over the range of noise exposure values typical of urban environments.

- The signal to noise ratio, rather than the absolute level, of noise events may be the more effective determinant of sleep disturbance. If outside ambient levels dominate the noise environment of sleeping quarters, closing a window may reduce aircraft noise levels and ambient levels in sleeping quarters about equally, leaving the signal to noise ratio of intruding sounds largely unaffected.

These potential explanations are not mutually exclusive.

6.8 Discussion of Self-Report Data

The 10 questionnaire items, as a whole, poorly predicted behavioral awakenings. However, number of recalled awakenings was strongly related to actual number of behavioral awakenings. Almost 50% of the variance in behavioral awakenings could be predicted from the number of recalled awakenings. It is not clear that recall of awakenings in the morning would reflect actual awakenings as accurately, however, in the absence of an active behavioral response at the time of awakening. If the act of pushing a button enhances recall of awakening, then it may be the button push rather than the awakening *per se* that is remembered.

Behavioral awakenings were also reliably associated with ratings of tiredness the previous night. The odds that a noise event would awaken a participant increased by a factor of 1.26 with each scale unit increase in tiredness the previous night.

Correlations among self-report items were not particularly strong, with few associations accounting for more the 10% of shared variance. The strongest association was a negative correlation between morning report of time spent awake and how well the participant slept. This association accounted for about 20% of shared variance.

No reliable differences in behavioral awakening were noted among sites. Several self-report responses did differ, however. Reported sleep quality and number of recalled awakenings were greatest at LAX. Reports of time spent awake and tiredness the previous night were greatest at Castle AFB. Reports of annoyance due to aircraft noise were greater at LAX and Castle AFB than at control sites.

6.9 Relationship between Findings of Current and Prior Studies

Figure 28 plots data from the current study along with data from the six field studies reviewed by Pearsons *et al.* (1989) and the data reported by Ollerhead *et al.* (1992). The current findings are generally consistent with those of prior field studies. Sleep is a sufficiently complex physiological process that its properties can be measured in a great many ways, however, so that detailed comparisons of current and prior findings are highly sensitive to differences among studies in definitions of sleep disturbance, differences in noise measurement procedures, and differences in analytic approaches. For example, Pearsons, Fidell, Bennett, Friedmann, and Globus (1974) reported an average of only three electroencephalographically defined awakenings per night in a small set of observations in the vicinity of Los Angeles International Airport. In an effort to relate actimetric observations of sleep disturbance to EEG-based observations, Ollerhead *et al.* (1992) adopted a definition of sleep disturbance that was sensitive both to shifts from deeper to lighter sleep states and to momentary awakenings. Thus, Ollerhead *et al.* observed about 45 "awakenings or arousals" per night, of which 40% (18) were thought to be "awakenings".
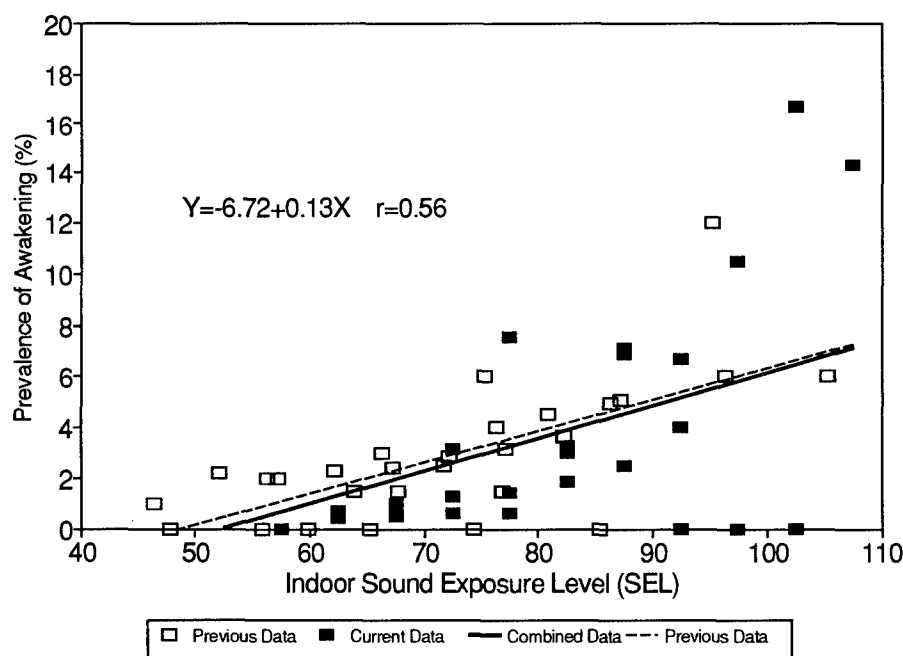
Figure 28   *Composite of data from current study with findings of prior sleep disturbance field studies. (Regression formula represents combined data.)*

An "awakening" so defined may have persisted for as little as ten seconds. Although momentary departures from light sleep into an electroencephalographically detectable state of wakefulness may be discriminated with some accuracy by researchers, test participants are unlikely to be fully aware of transient awakenings, nor to recall them in the morning. The large nightly numbers of

actimetrically-defined "awakenings" described by Ollerhead *et al.* are thus not directly comparable with the smaller numbers of behaviorally confirmed awakenings observed in the current study. Likewise, differences in electrode placement, sleep stage classification algorithms, or individual differences employed by Pearsons *et al.* (1974) and by Ollerhead *et al.* (1992) may all be partially responsible for the apparent discrepancy (3 vs. 18 per night) in "awakening" rates in these two studies.

A somewhat more direct comparison can be made between self-reported awakening rates observed by Ollerhead *et al.* and in the current study. Test participants in the study of Ollerhead *et al.* recalled a total of 7262 awakenings during 5742 subject-nights of data collection, for a gross average of 1.3 recalled awakenings per night. No awakenings at all were recalled on 57% of the nights, however, so that the average awakening rate for the 43% of the nights on which any awakenings were recalled was 2.9 per night. The average rate of behaviorally confirmed awakenings in the current study was slightly more than two per night. Since the number of behaviorally confirmed awakenings did not differ significantly from the number of recalled awakenings in the present study, general agreement with the findings reported by Ollerhead *et al.* appears to be good in this area.

The average of 2.07 behaviorally confirmed awakenings per night in the present study represents 0.26 awakenings per hour for the average night's sleep of slightly less than eight hours. This figure is similar to the spontaneous awakening rate observed by Horonjeff *et al.* (1982). Horonjeff *et al.* reported a spontaneous awakening rate of 0.20 per hour in an in-home study of more than 300 subject-nights of observations. The measure of awakening employed by Horonjeff et al. (a button press) was identical to that of the present study.

7 CONCLUSIONS

Because no effort was made to rigorously define the complete population exposed to nighttime noise exposure, nor to obtain a representative sample of any wider population, conclusions drawn from the present study apply strictly only to test participants. To the extent that generalizations are made from the present findings, they should be restricted to the effects of noise on the sleep of long term residents of areas with stable nighttime noise exposure.

The following are among the major findings of the present study:

1) A statistically reliable relationship was observed between sound exposure levels of individual noise intrusions in sleeping quarters and behaviorally confirmed awakening within five minutes of their occurrence. This relationship accounted for only about 30% percent of the variance in the awakening data, however.

2) The acoustic variable most closely related to sleep disturbance was the sound exposure level of individual noise events in sleeping quarters.

3) Although test sites varied in outdoor noise exposure level over the range of levels of principal interest for environmental analysis purposes, the prevalence of awakening among test participants did not increase greatly with sound exposure levels of noise intrusions in sleeping quarters.

4) The following linear relationship predicts the prevalence of awakening among test participants from SEL values of noise events in sleeping quarters:
% Awakened = -10.24 + 0.167(SEL)

5) The linear relationship that predicts the prevalence of awakening was considerably smaller when based on one-minute L_{eq} values preceding behavioral responses:
% Awakened = -0.63 + 0.026(L_{eq}).

6) Sizable differences were observed in noise exposure within sleeping quarters of homes with essentially identical outdoor noise exposure.

7) The average spontaneous awakening rate among test participants at all sites was about two per night. This figure did not differ significantly across sites with widely varying levels of nighttime noise exposure.

8) The relationship between indoor sound exposure levels of noise events and awakenings accounts for only about a third of the variance in the behavioral awakening data. Accuracy of prediction of awakening could be improved by including the following nonacoustic predictor variables as well: age, time since retiring, tiredness, ambient sound level in sleeping quarters, rate of spontaneous awakenings, and duration of residence.

9) Cessation of flight operations at the military airfield on weekend nights reduced the intensity of daily self-reports of annoyance, but was not associated with any significant difference in total behavioral awakening rates.

10) Indoor SEL accounted for less than half the predictable variance in behavioral awakening in a logistic regression model including other predictors.

11) For reserach purposes, the logistic regression equation which best predicts awakening is:

$$Probability(awakening) = \frac{e^u}{1 + e^u}$$

where:

$u = -6.361 + 0.058(\text{indoor SEL of noise event})^*$
$- 0.055(\text{ambient noise level in sleeping quarters})^* - 0.295(\text{spontaneous awakening rate})^*$
$+ 0.059(\text{elapsed time since retiring})^* + 0.002(\text{duration of residence})^*$
$+ 0.008(\text{study night}) - 0.048(\text{gender}) - 0.021(\text{age})^* + 0.047(\text{alcohol consumption})$
$- 0.082(\text{medications}) + 0.233(\text{self report of tiredness})^* + 0.171(\text{noise source})$

$(^* p < .001)$

12) The current findings resemble those of prior field studies of noise induced sleep disturbance.

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GLOSSARY

Terms in this Glossary are defined in the sense in which they are used in the body of this report, not necessarily in their broadest sense.

α: The probability of making a Type I error (q.v.).

Adjusted R^2: A correction to R^2 (q.v.) to compensate for inflation associated with small samples.

AL_{max}: Abbreviation for maximum A-level (q.v.).

Annoyance: A general adverse attitude toward noise exposure.

ANOVA: Abbreviation for analysis of variance (q.v.).

A-weighted sound level: A single number index of a broadband sound that has been subjected to the A-weighting network (q.v.)

A-weighting network: A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of moderate sound pressure level.

β: The symbol for a standardized regression coefficient, indicating the change in standardized units in a criterion variable with a standard deviation change in a predictor variable. In multiple regression (q.v.), change is evaluated with all other predictor variables held constant.

B: The symbol for an unstandardized regression coefficient, indicating the change in a criterion variable predicted from a one-unit change in a predictor variable. In multiple regression (q.v.), change is evaluated with all other predictor variables held constant.

Bivariate regression: Statistical technique for assessing the prediction of a continuous dependent variable from a single continuous independent variable, and the correlation between the variables.

Blocking variable: Variable (e.g., gender) which is controlled by conducting parallel analyses at each level (e.g., women and men).

Confidence interval: The range of population values of a statistic (e.g., a mean or regression line) that is reasonable within some probability level.

Confounding: A potential cause (the confound or confounder) of a response has not been controlled and, therefore, cannot be isolated from the presumed causal agent (noise exposure).

Covariate: Variable for which statistical adjustment or control has been made.

C-weighted Level: A single number index of a broadband sound that has been subjected to the C-weighting network (q.v.).

C-weighting network: A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of high sound pressure level. Essentially limits the bandwidth to include only unweighted 1/3 octave band levels from 31.5 to 8000 Hz.

d': Abbreviation and symbol for the scalar index of signal detectability

Day-Night Average Sound Level: A 24-h energy average sound level with a 10 dB adjustment for night (10 PM - 7 AM) time.

dB: Abbreviation for decibel (q.v.).

decibel: Unit measure of sound pressure level and other kinds of levels. It is expressed mathematically as the product of 10 times the logarithm to the base 10 of the ratio of a quantity of interest to a reference quantity.

Dependent variable: The response variable (effect) in a statistical analysis.

DNL: Abbreviation for Day-Night Average Sound Level (q.v.).

Dosage-response relationship: A plot (and analysis) showing a response (e.g., prevalence of disease or awakening) to a dose of noise exposure; aka dosage-effect relationship.

η^2: In analysis of variance (q.v.) the proportion of variance in the dependent variable associated with the independent variable.

Effect size: In statistics, the estimated difference between two populations, divided by the common variability within a population, or the ratio of explained (systematic) variance to total variance.

Effective Perceived Noise Level: The perceived noise level of a single event that has been modified for the additional annoyance caused by duration and tones.

EPNL: Abbreviation for Effective Perceived Noise Level (q.v.).

Equivalent Noise Level: The sound level typical of the sound levels at a certain place during a stated time period. Technically, time-average sound level in decibels is the level of the mean-square

A-weighted sound pressure during the stated time period, with reference to the standard sound pressure of 20 micropascals.

Heteroscedasticity: Unequal variance in the dependent variable for different values of the independent variable. The opposite of homoscedasticity (q.v.).

Hierarchical multiple regression: A form of multiple regression (q.v.) in which variables enter a prediction equation in a research-specified sequence; each predictor is evaluated at its point of entry into the equation.

Homogeneity of variance: The assumption in analysis of variance that variability in the dependent variable is the same within all groups or conditions.

Homoscedasticity: The regression analog of homogeneity of variance, in which the assumption is that the variance of the dependent variable is constant for all values of the independent variable(s).

Hosmer-Lemeshow χ^2: An inferential goodness-of-fit test to assess how far a logistic regression (q.v.) model departs from observed data.

Independent variable: A presumed causal (or predictor) variable in a statistical analysis.

L_{10}: The level of noise that is exceeded 10 percent of the time.

L_{50}: The level of noise that is exceeded 50 percent of the time.

L_{eq}: Abbreviation for equivalent noise level (q.v.).

Linearity: The assumption in regression that all relationships among variables (independent and dependent) are linear.

Logistic regression: A statistical technique for assessing the probability of an outcome from a set of other variables.

Maximum A-level: The maximum A-weighted sound level in a given time period.

Multiple regression: A statistical technique for assessing the prediction of and correlation between one variable (the dependent variable) and a set of other variables (the independent variables).

Multivariate multiple regression: Multiple regression (q.v.) in which there is more than one criterion variable.

Null hypothesis: The hypothesis that no population differences or relationships among variables exist.

PNL: Abbreviation for perceived noise level (q.v.)

Perceived Noise Level: A single number index obtained by a computational procedure that combines the 24 one-third octave frequency band sound pressure levels in bands centered from 50 to 10,000 Hz to obtain a single level. The number computed by this calculation procedure gives an approximation to the perceived noise level as judged by subjective experiment on a fundamental psycho-acoustical basis. Perceived noise level is numerically equal to the sound pressure level of a reference sound that is judged by listeners to have the same perceived nosiness as the given sound. Perceived noise level is generally computed for each 0.5-second time interval during an aircraft flyover.

Power: Sensitivity of a statistical analysis to finding a true difference among populations or relationship among variables, defined as $1 - \beta$.

Probit transform: A transformation of proportions to reflect the value of the standard normal deviate below which that proportion is found.

r: Index of bivariate linear correlation, the relationship between two continuous variables.

R^2: Symbol for squared multiple correlation, the variance in the criterion variable that is predictable from the set of predictor variables in multiple regression (q.v.).

Reactivity: Biases in a research study associated with knowledge on the part of the participant that he or she is part of a study; behaving differently in a study than in real life.

Receiver operating characteristic (ROC) curve: A plot of the sensitivity of a receiver showing the proportion of hits (decision that an event has occurred when it has in fact occurred) as a function of false alarms (decision that an event has occurred when it has not in fact occurred). The area between the ROC curve and the major diagonal is a measure of d' (q.v.).

Residual: The difference between an observed value and one that is predicted on the basis of a statistical analysis.

SEL: Abbreviation of sound exposure level (q.v.).

Single-sided test: Inferential test in which differences only in one direction between two populations are evaluated.

Sound exposure level: The level of sound accumulated over a given time period or event. It is particularly appropriate for a discrete event such as passage of an airplane, a railroad train, or a truck. Sound exposure level is not an average, but a special kind of sum. For example, for steady sounds, time-average sound level is constant; in contrast, sound exposure level increases in direct proportion to the logarithm of the ratio of the duration of the measurement time in seconds to the reference duration of 1.0 second. Technically, sound exposure level in decibels is the level of the time integral of A-weighted squared sound pressure over a stated time interval or event, with reference to the square of the standard reference pressure of 20 micropascals and reference duration of 1.0 second.

Sound pressure level: A measure of sound taken as ten times the common logarithm of the square of the ratio of sound pressure to the reference sound pressure of 20 micropascals. The frequency bandwidth must be identified.

Standard multiple regression: The usual form of multiple regression in which all variables enter a prediction equation simultaneously and each is evaluated as if it entered last.

Statistical adjustment: Holding adjusted variables constant in order to reveal the unique effect of other variables. See covariate.

Subject-night: The amount of data collected from one subject for one night.

Two-sided test: Inferential test in which differences in either direction between two populations are analyzed.

Type I error: Declaring populations different when in fact they are not different, or relationships among variables to exist when they do not.

Type II error: Failure to declare populations different when in fact they are different, or failing to find relationships among variables when in fact they exist.

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APPENDIX A   DATABASE DESIGN

All information collected was stored in a relational database system that preserved time-linked associations among measurements of indoor sound levels, button pushes, and interview responses. A master table contains basic identification data linked via common fields to sub-tables which hold specific subsets of data. Figure A-1 is a schematic diagram of the database design.

INFO.DBF

Group	Site	Subject	House Num	Gender	Age	Months	Start date

NIGHT.DBF

Group	Site	Subject	Date	Time	Datetime	Q_1	....	Q_n

MORNING.DBF

Group	Site	Subject	Date	Time	Datetime	Q_1	....	Q_n

BUTTON.DBF

Group	Site	Subject	Date	Time	Datetime

SLEEP.DBF

Group	Site	Subject	Sleepdate	Sleeptime	Datetime 1	Wakedate	Waketime	Datetime 2

ONE_MIN.DBF

Group	Site	Date	Time	Datetime	L_{eq}

EXCEED.DBF

Group	Site	Date	Time	Datetime	Duration	L_{eq}	L_{max}	SEL

Figure A-1   *Database Structure for Sleep Study Data.*

A.1 Master Table

Unique identifying fields serve as links to interview and awakening data, and to information about the test participant's gender, age, and study site. The group, site, and subject number fields in this master table serve as links to tables containing acoustic and noise event data as well as behavioral response data. Table A-1 outlines the structure of the master INFO.DBF file.

Table A-1   *Structure of the Master Database Table.*

INFO.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code designating each study group. A=Control, C=Castle AFB, L=LAX.
SITE	CHARACTER	1	A code designating the study site within each group.
SUBJECT	CHARACTER	3	Subject Number.
HOUSE_NUM	CHARACTER	2	Number representing each house, regardless of group. Used for statistical analyses.
GENDER	CHARACTER	2	A code designating gender of subject. 0=MALE 1=FEMALE
AGE	CHARACTER	2	A field containing age of subject in years at the start of the study.
MONTHS	CHARACTER	4	Length of time subject has lived at current address (in months).
START_DATE	CHARACTER	20	Date subject began participation in study.

A.2 Interview Data

Interview responses are stored in two separate sub-tables (NIGHT.DBF and MORNING.DBF) linked through the group, site and subject number codes. These sub-tables include the date, time, and responses to interview questions administered prior to retiring at night and after awakening in the morning. Table A-2 and Table A-3 show the structure of these tables.

Table A-2 *Structure of Table Containing Evening Interview Data.*

NIGHT.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code identifying each study group.
SITE	CHARACTER	1	A code identifying the study site within each group.
SUBJECT	CHARACTER	3	Subject number.
DATE	DATE	8	A DATE field containing the date of the evening interview.
TIME	CHARACTER	8	A field containing the time of the evening interview.
DATETIME	NUMERIC	20	A field containing a numeric representation of DATE and TIME used for database sorting and analyses.
Q1	CHARACTER	1	This field holds the coded answer to the first interview question.
...		1	
Qn	CHARACTER	1	This field holds the coded answer to the last interview question.

Table A-3   *Structure of Table Containing Morning Interview Data.*

MORNING.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code identifying each study group.
SITE	CHARACTER	1	A code identifying the study site within each group.
SUBJECT	CHARACTER	3	Subject number.
DATE	DATE	8	A DATE field containing the date of the morning interview.
TIME	CHARACTER	8	A field containing the time of the morning interview.
DATETIME	NUMERIC	20	A field containing a numeric representation of DATE and TIME. Used for database sorting and analyses.
Q1	CHARACTER	1	This field holds the coded answer to the first interview question.
...		1	
Qn	CHARACTER	1	This field holds the coded answer to the last interview question.

A.3 Sleep Data

A table called SLEEP.DBF contains information about when subjects went to sleep and woke up during study nights. The structure of this table is shown in Table A-4.

Table A-4   *Structure of Table Containing Sleep Data.*

SLEEP.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code designating each study group. A=Control, C=Castle AFB, L=LAX
SITE	CHARACTER	1	A code designating the study site within each group.
SUBJECT	CHARACTER	3	Subject number.
SLEEPDATE	DATE	8	Date subject went to sleep.
SLEEPTIME	CHARACTER	8	Time subject went to sleep.
DATETIME 1	NUMERIC	20	A field containing a numeric representation of SLEEPDATE and SLEEPTIME used for database sorting and analyses.
WAKEDATE	DATE	8	Date subject woke up.
WAKETIME	CHARACTER	8	Time subject woke up.
DATETIME 2	NUMERIC	20	A field containing a numeric representation of WAKEDATE and WAKETIME used for database sorting and analyses.

A.4 Awakening Data

A table called BUTTON.DBF contains data about awakenings that occurred during the study nights. The structure of this table is shown in Table A-5. This table contains only group and site information and dates and times of awakenings.

Table A-5   *Structure of Table Containing Awakening Data.*

BUTTON.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code identifying each study group.
SITE	CHARACTER	1	A code designating the study site within each group.
SUBJECT	CHARACTER	3	Subject number.
DATE	DATE	10	A DATE type field containing the date of the awakening.
TIME	CHARACTER	8	A field containing the time of the awakening.
DATETIME	NUMERIC	20	A field containing a numeric representation of DATE and TIME used for database sorting and analyses.

A.5 Acoustic Epoch Data

Information about the various noise metrics is contained in a set of three tables. Summary metrics were computed for consecutive 1, 2, and 5 minute epochs, yielding three data tables for noise levels measured inside residences. The structure of each of these three tables is identical. Each record contains one epoch of data. The form of this set of three tables is shown in Table A-6. Note that these tables do not contain raw information from noise monitors, but rather the results of considerable data reduction and post-processing.

Table A-6   *Structure of Acoustic Epoch Tables.*

ONE_MIN.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	1	A code identifying each study group.
SITE	CHARACTER	1	Code designating location of study site.
DATE	CHARACTER	10	A field containing the date of the epoch.
TIME	CHARACTER	8	A field containing the time of the epoch.
DATETIME	NUMERIC	20	A numeric representation of DATE and TIME used for database sorting and analyses.
LEQ	NUMERIC	6	The L_{eq} of each epoch.

A.6 Acoustic Event Data

A table called EXCEED.DBF contains noise event data. The structure of this table is shown in Table A-7.

Table A-7 *Structure of Acoustic Events Table.*

EXCEED.DBF			
Field Name	**Data Type**	**Field Length**	**Description**
GROUP	CHARACTER	2	A code identifying each study group.
SITE	CHARACTER	2	Code designating location of study site.
DATE	CHARACTER	10	A field containing the date of the event.
TIME	CHARACTER	8	A field containing the time of the event.
DATETIME	NUMERIC	20	A numeric representation of DATE and TIME used for database sorting and analyses.
DURATION	CHARACTER	10	Duration of the event.
LEQ	NUMERIC	6	The L_{eq} of the event.
LMAX	NUMERIC	6	Maximum A-level of the event.
SEL	NUMERIC	6	The SEL of the event.

APPENDIX B   RECRUITING PROCEDURES AND INSTRUCTIONS TO TEST PARTICIPANTS

B.1 Recruiting of Test Participants

The initial mailing to prospective test participants near Castle Air Force Base included a letter of explanation on Air Force letterhead, a letter on BBN letterhead, and a return form with a stamped, pre-addressed envelope.

The wording of the Air Force letter was as follows:

"As part of a federally-mandated effort to evaluate and establish environmental standards, the U.S. Air Force is sponsoring research this summer on sleep disturbance. Castle AFB has been selected as one of several sites for investigation.

BBN Systems and Technologies of Los Angeles is the contractor for the study here. Their representatives are currently seeking interested parties to participate in the month long study. Your participation in this study will assist the Air Force in its continuing efforts to understand environmental impacts of aircraft noise on those living near bases.

If you have any questions, please feel free to call (XXX)."

The wording of the BBN letter was as follows:

"BBN Systems and Technologies is conducting a scientific study during August and September of sleep disturbance in your neighborhood. As described in the attached letter, this study is being conducted for the United States Air Force.

People who take part in this study will push a button if they wake up at night. We would like to tell you more about this study, and to find out if you or other members of your family might be interested in taking part in it. Each person who participates will be paid $100 at the end of the study period.

If you are interested in learning more about the study, please fill out and mail the attached form in the stamped envelope. Returning the form does not obligate you to take part in the study. BBN will contact you to explain details of the study and answer any questions you may have. If you wish to speak to someone about the study, please call (XXX)."

Prospective test participants were asked to provide information useful for contacting them and assessing their suitability for participation on the returned form.

B.2 Instructions to Test Participants

Test participants were sent an instructions booklet following a telephone interview during which (1) they were informed about the study and their roles as test participants, (2) their willingness and suitability as test participants were determined, and (3) an initial equipment installation appointment was set up. Follow-up telephone calls were made to answer any additional questions test participants may have had upon examining the instructions booklet.

The contents of the instruction booklet are reproduced on the following pages.

YOUR JOB IN THE SLEEP STUDY

This booklet explains what you are expected to do in the sleep study.

You have three things to do every day:

1. Answer the Nighttime Questionnaire on the small computer before you go to bed for the night.

2. Push the red button if you wake up for any reason during the night.

3. Answer the Morning Questionnaire on the small computer when you get out of bed in the morning.

WHAT TO DO JUST BEFORE YOU GO TO BED AT NIGHT:

1. Make sure that the two black cables are firmly plugged into the small computer, and that the computer is plugged into a wall outlet. Also, check to see that the noise monitoring equipment is plugged into an outlet.

2. Make sure that the red button you push when you wake up is within easy reach of your bed.

3. Open the hinged top of the small computer by lifting the lid from the front. If the screen is blank, press the "ON" button in the upper right-hand corner of the keyboard.

4. Press the "F10" key (toward the right of the top row of buttons) to start the nighttime questionnaire.

5. Answer each question by picking the number which best describes your answer, then press the "ENTER" key. Turn to page 7 for an explanation of each of the nighttime questions.

    If you make a mistake in your answer, you can correct it by pressing the "ESC" key in the upper left corner of the keyboard and answering the question again.

6. After you have answered all of the questions and *you are ready to go to sleep*, press "F10" again to set the computer for the night. You may leave the computer lid open or closed as you like. *Do not* turn the computer off.

The questionnaire should take less than a minute to complete. You have to answer the questions only once each night as you are about to go to bed, *not* each time you wake up during the night.

WHAT TO DO DURING THE NIGHT:

1. Press the red button once, right away, *each* time you wake up for any reason at all during the night. If you stay awake for a while after pushing the button, *do not* press the button again.

2. If you forget to press the button when you wake up during the night, and you then stay awake for more than five minutes, *do not* press the button again.

3. If you stay awake for a while after you wake up during the night and you can't remember (or are not sure) if you pushed the button when you first woke up, *do not* press the button again.

   REMEMBER: Press the red button *ONCE*, as soon as you wake up, each time you wake up for any reason at all.

WHAT TO DO WHEN YOU WAKE UP IN THE MORNING:

1. As soon as you wake up in the morning press the red button once.

2. If you closed the lid of the small computer the previous evening, open it by lifting the lid from the front.

3. Press the "F10" key. You will then be asked to estimate how many times you woke up during the night. Press the number on the keypad in the lower right corner of the keyboard and press "Enter".

4. Answer each of the following questions by picking the number which best describes your answer, then pressing the "ENTER" key. Turn to page 8 for an explanation of each of the morning questions. If you make a mistake in your answer, you can correct it by pressing the "ESC" key in the upper left corner of the keyboard and answering the question again.

If you forget to answer the morning questionnaire when you get up, then answer the questions as soon as you remember.

WHAT TO DO IF YOU TAKE A NAP DURING THE DAY:

You don't have to do anything with the equipment if you take a nap during the day. There is no need for any interview or to push the button before or after napping.

IF YOU HAVE OTHER QUESTIONS:

If you have any questions about the study procedures or experience any difficulty in operating the computer, please call: **1-800-XXX-XXXX**

HOW TO ANSWER THE NIGHTTIME QUESTIONS:

There are only three questions to answer before you go to bed at night:

1.   How tired did you feel today?

Please pick the phrase that best describes how you felt throughout the entire day (not just at the time you are answering the question). Your choices are:

1.   Not at all tired
2.   Slightly tired
3.   Moderately tired
4.   Very tired
5.   Extremely tired

Press the number on the keypad in to lower right-hand corner of the keyboard corresponding to your choice.

2.   Did you drink any alcohol tonight?

Please answer YES if you drank any alcoholic beverages (beer, wine, cocktails, etc.) either with dinner or later this evening. Please answer NO if you did not.

3.   Did you take any medication tonight?

Please answer YES if you took any prescription or non-prescription medication (even aspirin) this evening. Please answer NO if you did not.

HOW TO ANSWER THE MORNING QUESTIONS:

1.   How many times did you wake up last night?

Please estimate the number of times you woke up last night. Type in the number and press "Enter".

2.   How well did you sleep last night?

Please tell us how well you slept last night. Your choices are:

1.   Not at all well
2.   Fairly well
3.   Moderately well
4.   Very well
5.   Extremely well

3. How tired do you feel this morning?

Please tell us how tired you feel right now, as you're getting up. Your choices are:

1. Not at all tired
2. Slightly tired
3. Moderately tired
4. Very tired
5. Extremely tired

4. How long did it take you to fall asleep?

Please estimate how long it took you to fall asleep when you first went to bed last night. Your choices are:

1. Less than 10 minutes
2. 10 - 20 minutes
3. 20 - 30 minutes
4. 30 - 60 minutes
5. more than an hour

5. How much were you awake last night?

Please estimate the total amount of time you were awake during the night after you first went to sleep. For example, if you woke up twice during the night and were awake for approximately five minutes each time, then you were awake for a total of about 10 minutes. In this case, you should answer "10-20 minutes". If you did not wake up at all during the night, or if you fell back to sleep quickly after awakening, answer "Less than 10 minutes." Your choices are:

1. Less than 10 minutes
2. 10 - 20 minutes
3. 20 - 30 minutes
4. 30 - 60 minutes
5. more than an hour

6. Were you awakened by aircraft noise?

If you woke up during the night, and you remember why you awoke, was it because you heard aircraft noise? If you aren't sure if aircraft noise woke you up, then your answer should be "Don't know". Your choices are:

1. Yes
2. No
3. Don't know

If you answer "No" to this question, you are done. If you answer "Yes" or "Don't Know", you will be asked the next question.

7. How annoyed were you by aircraft noise?

If you heard aircraft noise during the night (whether you were awakened by it or you were already awake), how annoyed were you by the noise? Your choices are:

1. Not at all annoyed
2. Slightly annoyed
3. Moderately annoyed
4. Very annoyed
5. Extremely annoyed

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APPENDIX C   IDENTIFICATION OF ANALYSIS EPOCH FOR SLEEP DISTURBANCE

The literature provides little guidance about the latency between the occurrence of a noise intrusion and its manifestation as sleep disturbance. In some laboratory studies (e.g., Collins and Iampietro, 1973, Ludlow and Morgan, 1972), numbers of awakenings are compared over periods (nights or parts of nights) in which different types of noises are presented. In other studies (e.g., Horonjeff, Bennett and Teffeteller, 1979; Kramer, Roth, Trindar & Cohen, 1971), noise levels are increased until the participant awakes, or remain virtually continuous throughout the night (e.g., Johnson, 1973). Further, in laboratory studies in which responses to individual noise intrusions are monitored, the criterion latency to behavioral response (or nonresponse) is not always reported (e.g., Collins & Iampietro, 1973).

Most studies which have measured sleep disturbance electroencephalographically (e.g., Lukas & Dobbs, 1972; Stevenson & McKellar, 1989) have used the Rechtschaffen & Kale (1968) scoring system. This system has inherent analysis latencies, including (1) a change in sleep state within half a minute of occurrence of a noise intrusion, and (2) awakening "usually" within 1 minute of occurrence of a noise intrusion. The shorter latency (30 s) is typically applied to heart rate or body movement. The latency for awakening is sometimes modified to 1.5 minutes. Horonjeff *et al.* (1979) associate a small percentage of awakening responses to steady state exposure with latencies of 13 minutes or greater.

In field studies which depend on fortuitous noise exposure, disturbing noise events must be sought retroactively from responses. Other field studies simply compare noisy with quieter environments, with no reports of effects of individual events (e.g., Ando & Hattori, 1977; Ohrstrom, Rylander & Bjorkman, 1988). Those studies in which retroactive assessment has been reported (e.g., Pearsons, Bennett & Fidell, 1973, Vallet, Gagneux & Simmonnet, 1980) use a 1 or 2 minute analysis interval for awakening. That is, once a response has occurred, the sounds occurring one (or two) minutes before the response are considered to be the proximal cause. Field studies employing EEG recordings (e.g., Vallet *et al.*, 1980; Vernet, 1979) generally use 1 to 1.5 minute analysis epochs, even when there is no other basis for associating a particular noise event with a subsequent change in sleep state.

Three analysis epochs were utilized in the current study: 1, 2, and 5 minutes. The need for multiple analysis epochs is illustrated in Figure C-1 through Figure C-5 with respect to three time series of hypothetical data. The top trace in each figure is a time series of A-weighted sound pressure levels measured outside a test participant's sleeping quarters. The middle trace in each is a similar time series of sound pressure levels measured in the test participant's sleeping quarters. The bottom trace is an event marker representing a behavioral indication of sleep disturbance, such as a button push upon awakening.
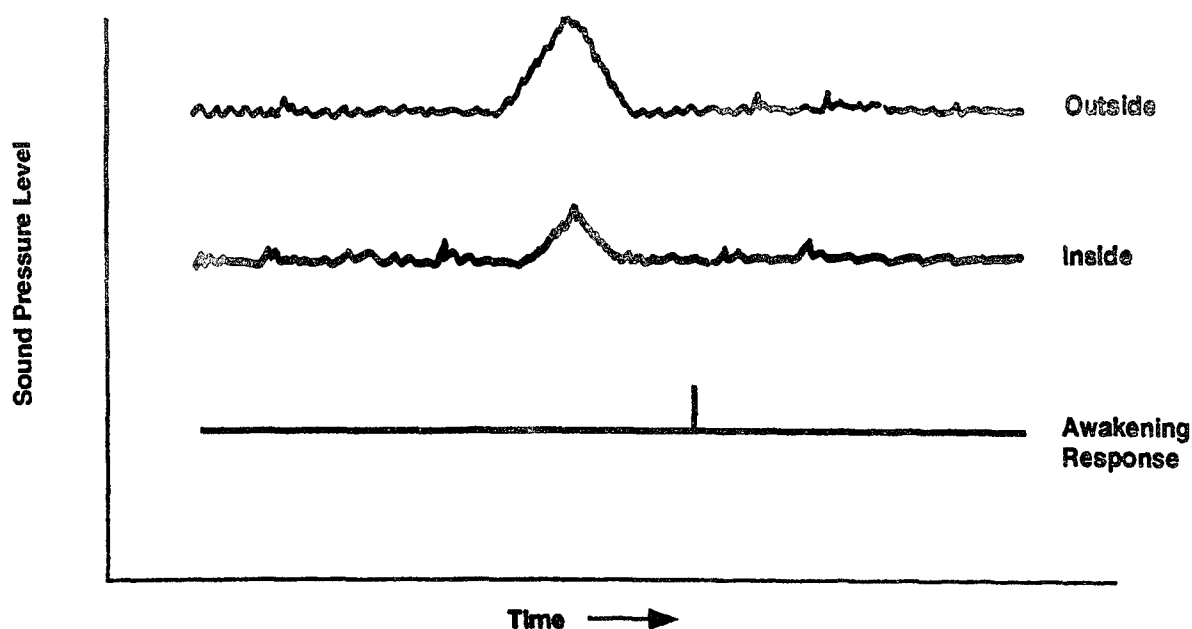
Figure C-1 *Case 1 showing a high signal-to-noise ratio event occurring outdoors.*

Case 1, illustrated in Figure C-1, is the one which comes to mind first. A single, high signal-to-noise ratio event (probably an overflight, given the site selection criteria), isolated in time from all other noise events, is registered outside a residence, and at a lower level, within the bedroom. This obvious noise intrusion is followed in close temporal proximity by a behavioral indication of sleep disturbance. The analysis in this case is straightforward: various measures of the noise event as recorded either inside or outside are associated with a sleep disturbance within a short period of time - say, one minute - to develop a dosage-response relationship from multiple events of this sort.

Not all behavioral indications of sleep disturbance are as unambiguously associated with noise events in an uncontrolled exposure study, however. For example, in Case 2, illustrated in Figure C-2, an outside noise event occurs, is recorded both outside and inside, but a second indoor noise event occurs in close temporal proximity. With which event(s) should an awakening be associated?

Likewise, multiple events may occur in close temporal proximity, either indoors or outdoors or both, as in Case 3, illustrated in Figure C-3. One or more of these may be associated with aircraft flyovers, neighborhood noise sources, or even simultaneously-occurring indoor noise events. Should a short term L_{eq} also be considered as a potential index of exposure under such conditions? If so, for what period(s) of time should values of this metric be calculated?
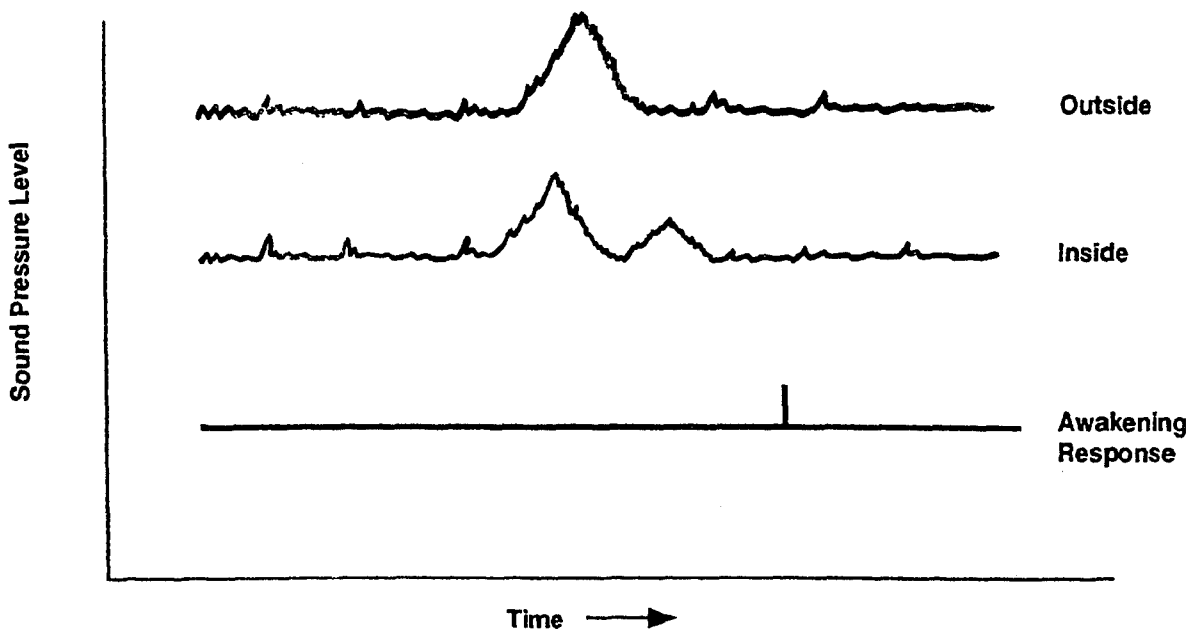
98

Figure C-2   *Case 2 depicting outdoor and indoor noise events occurring in close temporal proximity.*
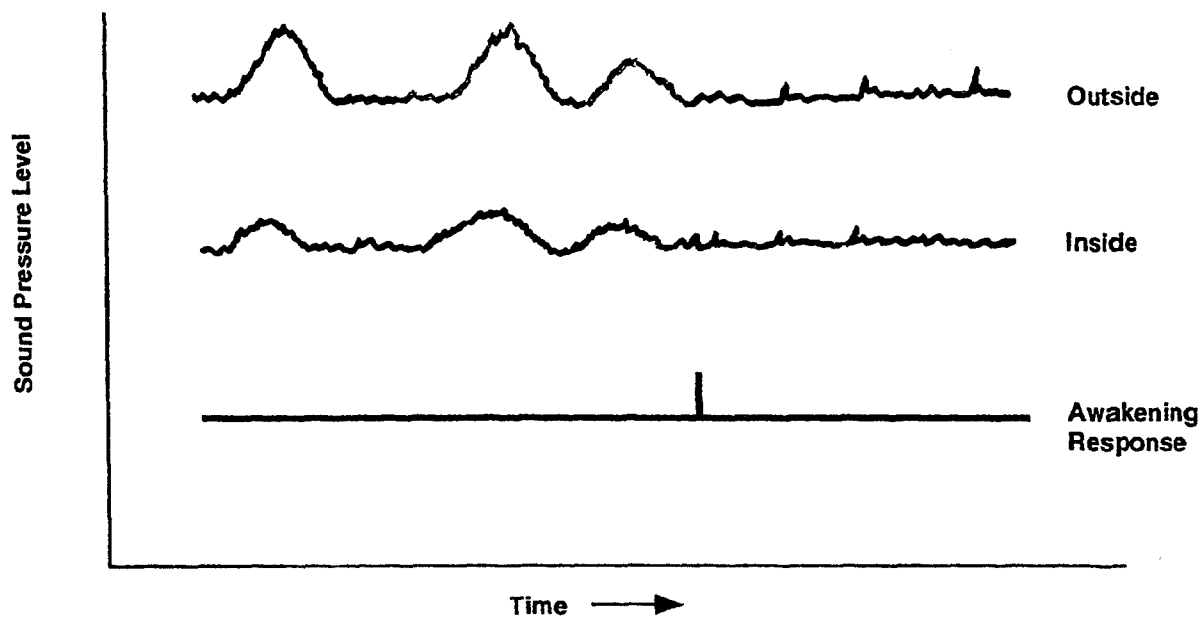

Figure C-3   *Case 3 depicting multiple events occurring in close temporal proximity.*

Case 4, depicted in Figure C-4, illustrates the occurrence of an outdoor noise event followed by an even higher level indoor noise event. How may it be determined which (if either) of these

events created the subsequent sleep disturbance? In Case 5, illustrated in Figure C-5, there is no discernable noise event to associate with a seemingly spontaneous indication of sleep disturbance. Should this response be categorized as non-acoustic in origin, or might a general elevation of the customary ambient level be responsible for the awakening?
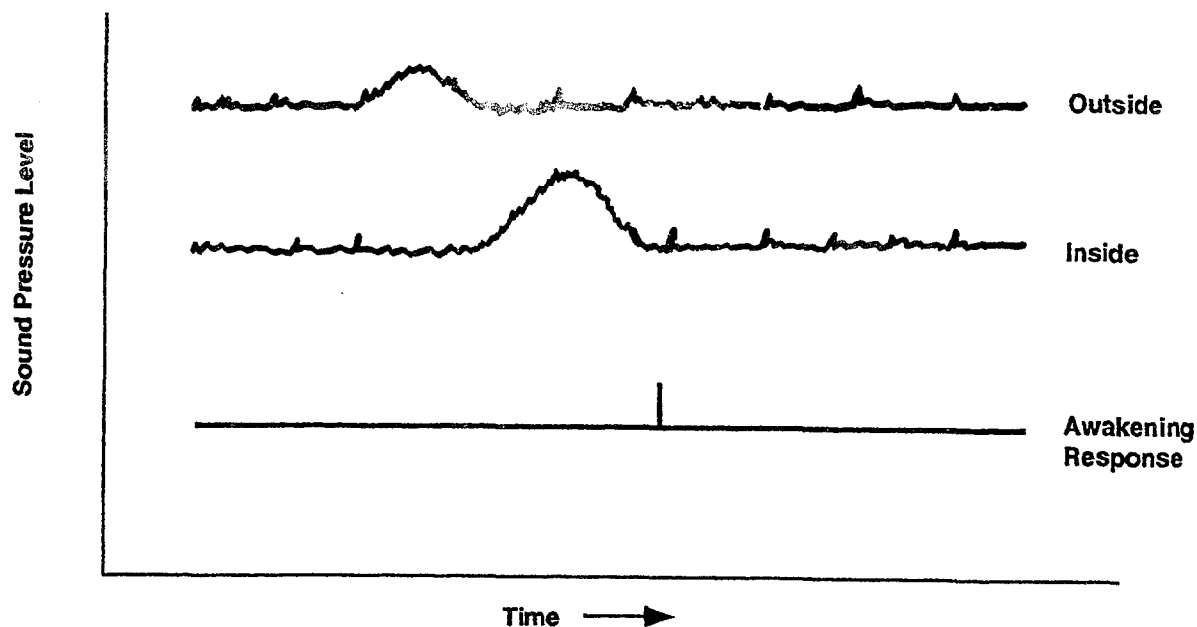

Figure C-4   *Case 4 depicting an outdoor noise followed by a high-level indoor event.*

Since the investigator in an observational study does not control any of the noise exposure described above, procedures for analyzing the relationship between sleep disturbance and noise exposure in such data sets must be adequate to support testing of a range of hypotheses about the origins of behavioral responses. For example, is the correlation between noise exposure and sleep disturbance greater when noise events occurring more than a minute prior to the response are excluded from the analysis? Should responses be categorized by the number of immediately preceding definable noise intrusions? If so, during what antecedent period(s)?
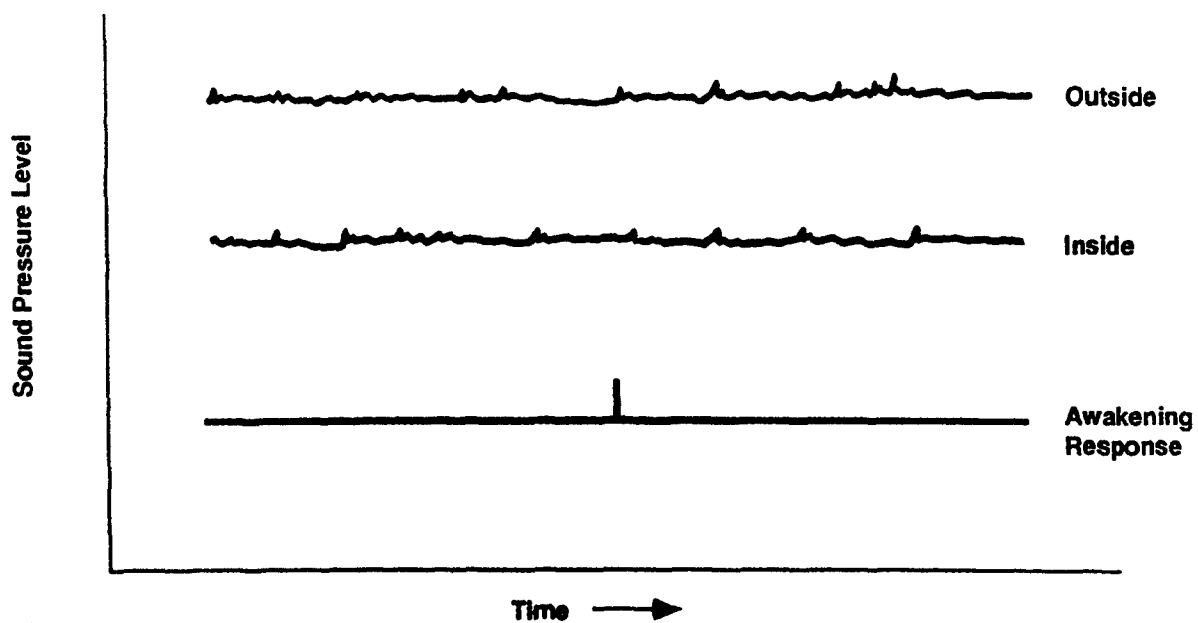
100

Figure C-5   *Case 5 depicting spontaneous (non-noise related) awakening.*

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APPENDIX D   SUMMARY OF INTERVIEW DATA

D.1   Summary of Nighttime Interviews

Figure D-1 through Figure D-3 describe the results of the nighttime questionnaire based on data from 931 subject nights.

D.2   Summary of Morning Interviews

Figure D-4 through Figure D-9 describe the results of the morning questionnaire based on data from 931 subject nights.
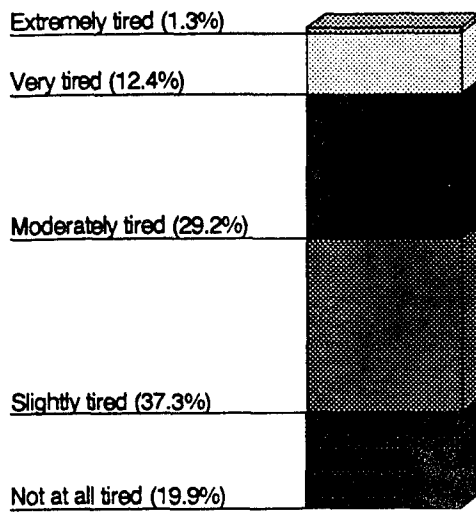
How tired did you feel today?

Extremely tired (1.3%)

Very tired (12.4%)

Moderately tired (29.2%)

Slightly tired (37.3%)

Not at all tired (19.9%)

Figure D-1   *Summary of responses to: "How tired did you feel today?"*

Did you drink any alcohol tonight?

No (87.6%)

Yes (12.4%)
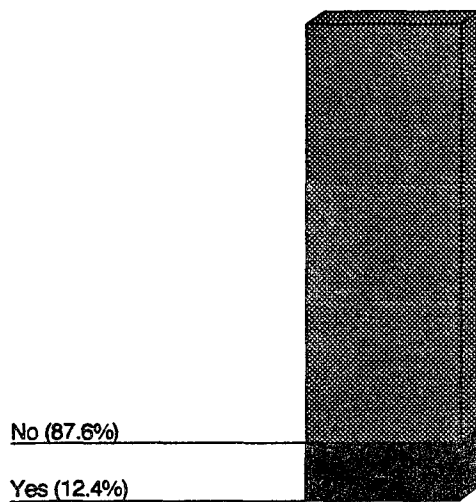
Figure D-2   *Summary of responses to: "Did you drink any alcohol tonight?"*

Did you take any medication tonight?

No (81.2%)

Yes (18.8%)
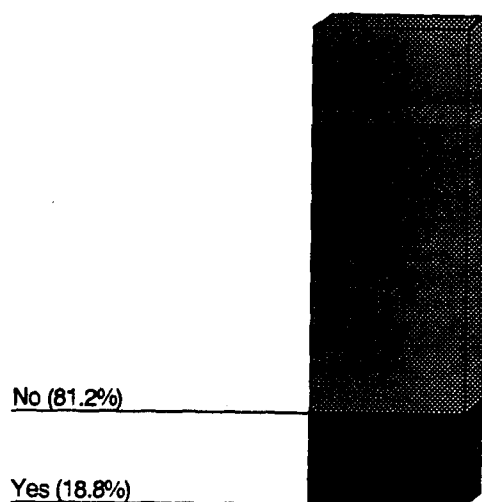
Figure D-3   *Summary of responses to: "Did you take any medication tonight?"*

How well did you sleep last night?

Extremely well (5.9%)

Very well (33.2%)

Moderately well (26.5%)

Fairly well (27.2%)
Not at all well (7.2%)
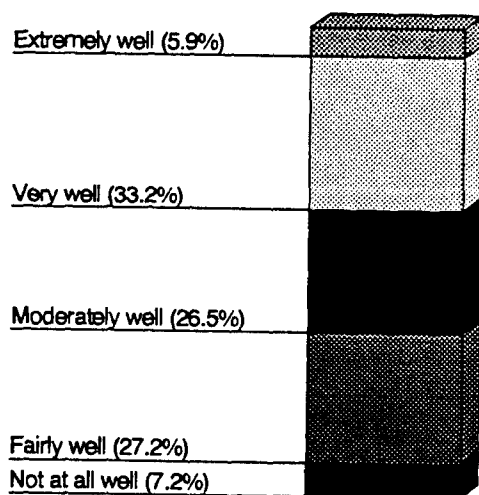
Figure D-4   *Summary of responses to: "How well did you sleep last night?"*

How tired do you feel this morning?

Extremely tired (1.0%)

Very tired (7.5%)
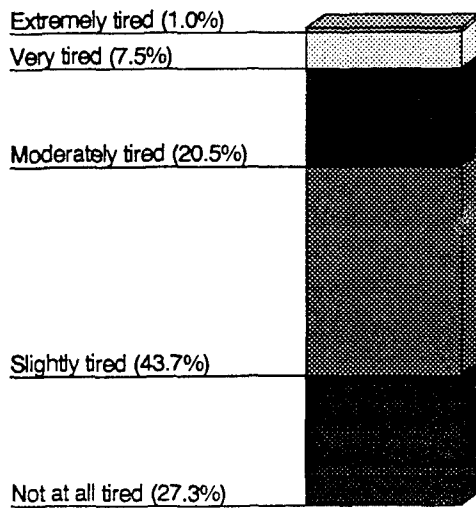
Moderately tired (20.5%)

Slightly tired (43.7%)

Not at all tired (27.3%)

Figure D-5 *Summary of responses to: "How tired do you feel this morning?"*

How long did it take you to fall asleep?

more than an hour (3.4%)

30 - 60 minutes (5.0%)

20 - 30 minutes (12.1%)

10 - 20 minutes (31.2%)

Less than 10 minutes (48.3%)

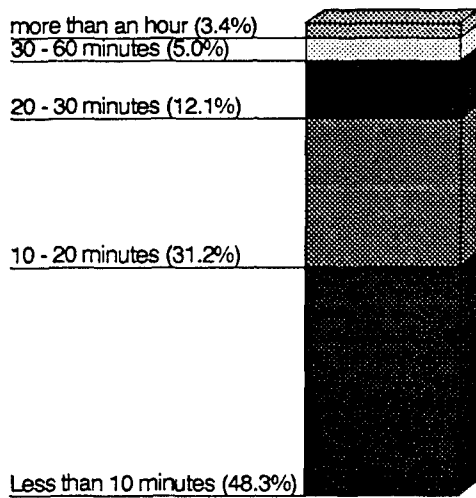**Figure D-6** *Summary of responses to: "How long did it take you to fall asleep?"*

How much were you awake last night?

more than an hour (3.9%)
30 - 60 minutes (7.8%)

20 - 30 minutes (13.7%)

10 - 20 minutes (26.2%)

Less than 10 minutes (48.3%)
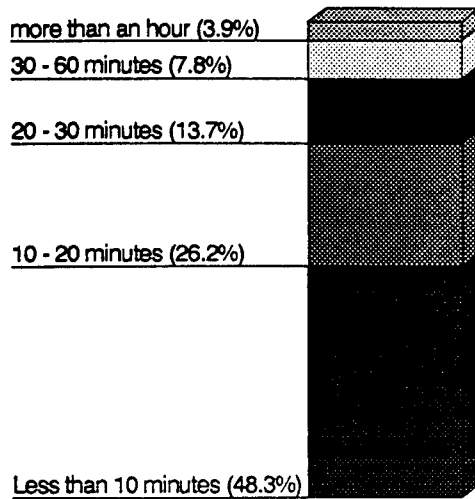
Figure D-7 *Summary of responses to: "How much were you awake last night?"*

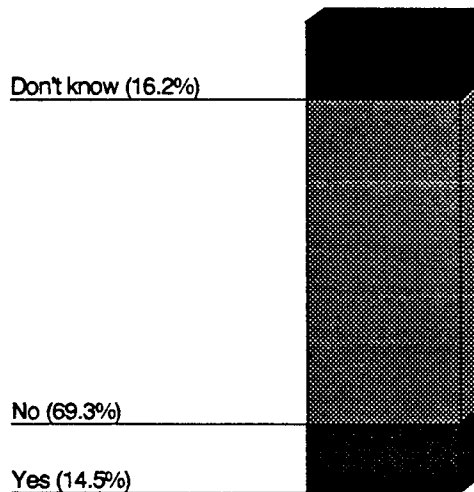# Were you awakened by aircraft noise?

Don't know (16.2%)

No (69.3%)

Yes (14.5%)

Figure D-8 *Summary of responses to: "Were you awakened by aircraft noise last night?"*

How annoyed were you by aircraft noise?

Extremely annoyed (4.7%)

Very annoyed (11.7%)

Moderately annoyed (17.9%)

Slightly annoyed (33.3%)
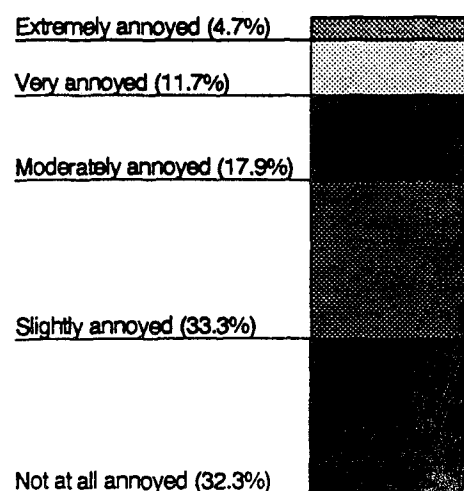
Not at all annoyed (32.3%)

Figure D-9   *Summary of responses to: "How annoyed were you by aircraft noise?"*